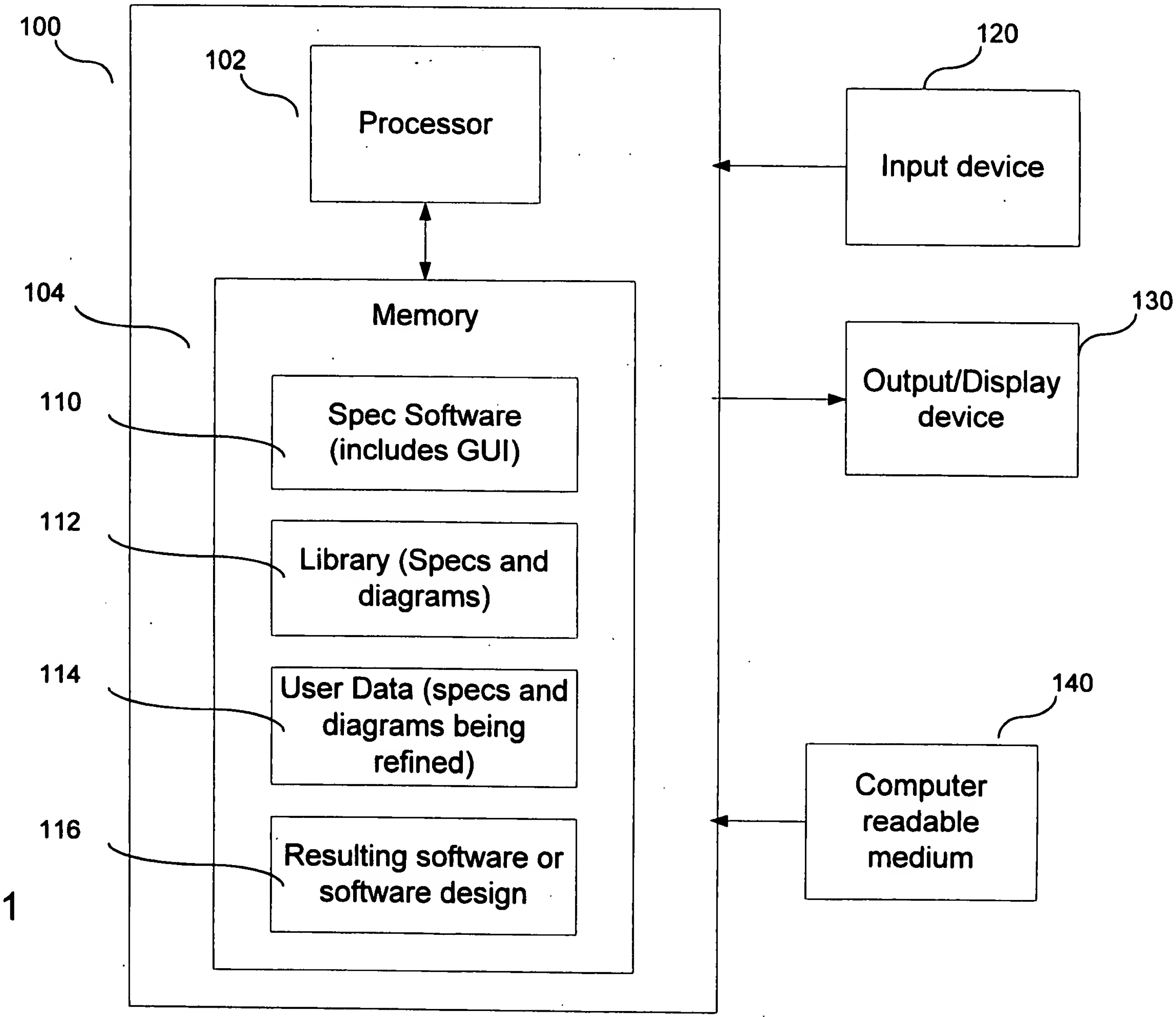


Fig. 1

09655173.021900

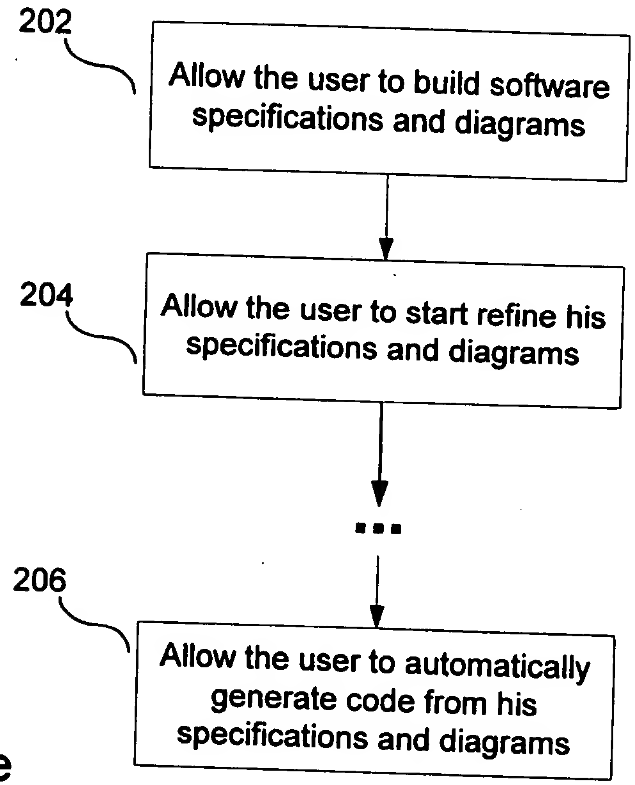


Fig. 2(a)
Spec Software

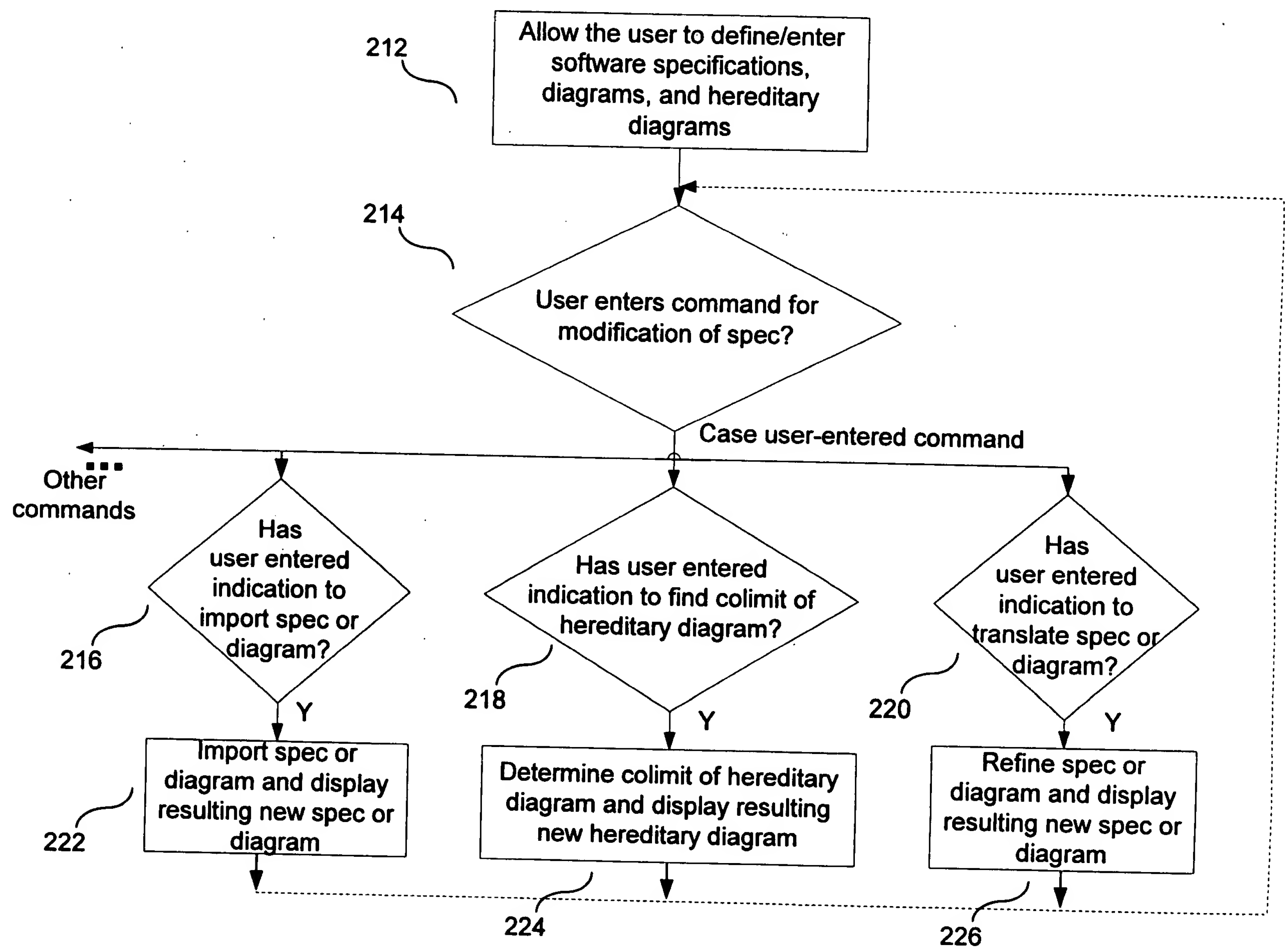
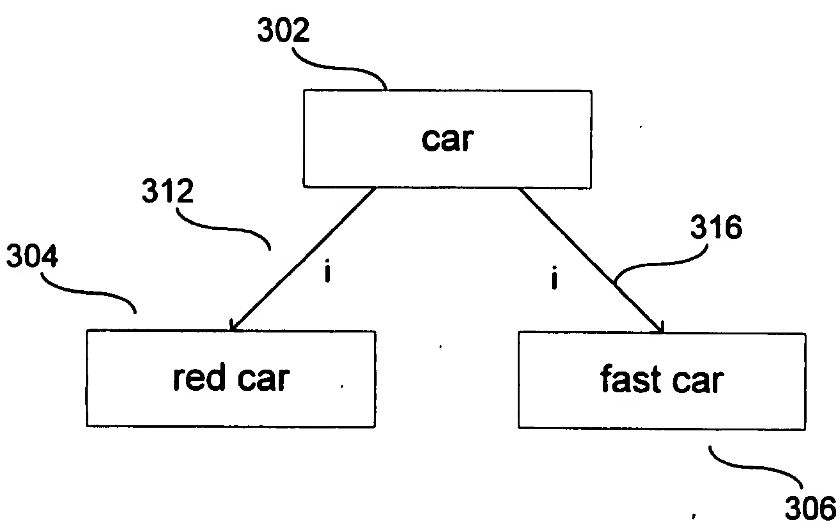
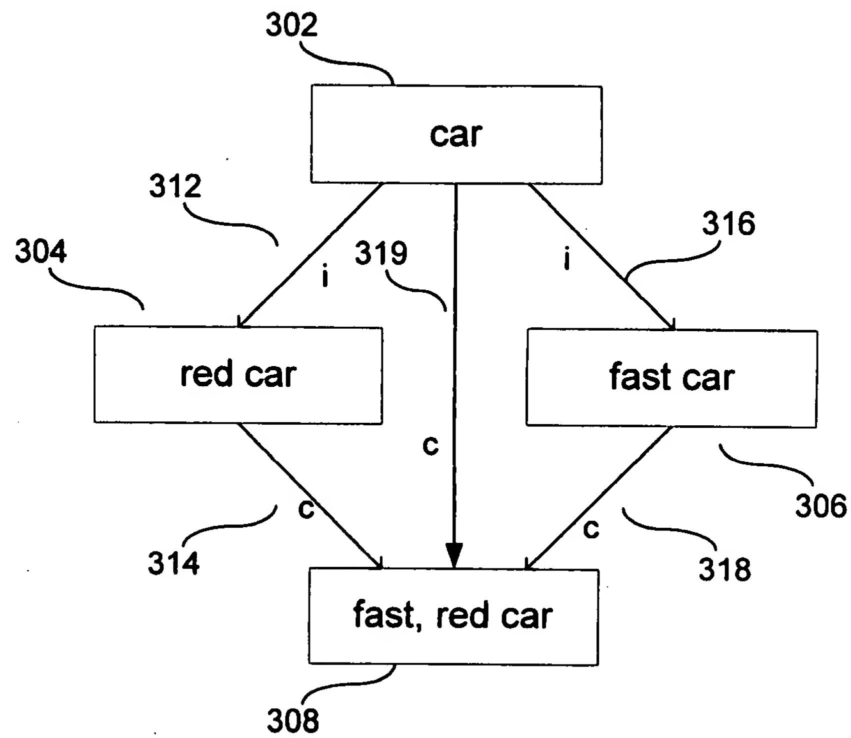


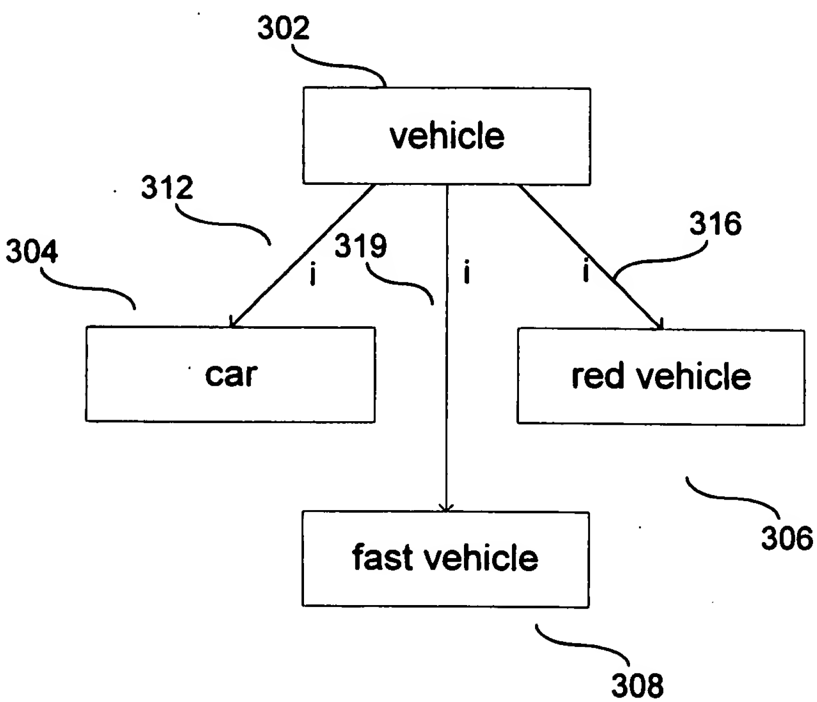
Fig. 2(b)
Spec Software



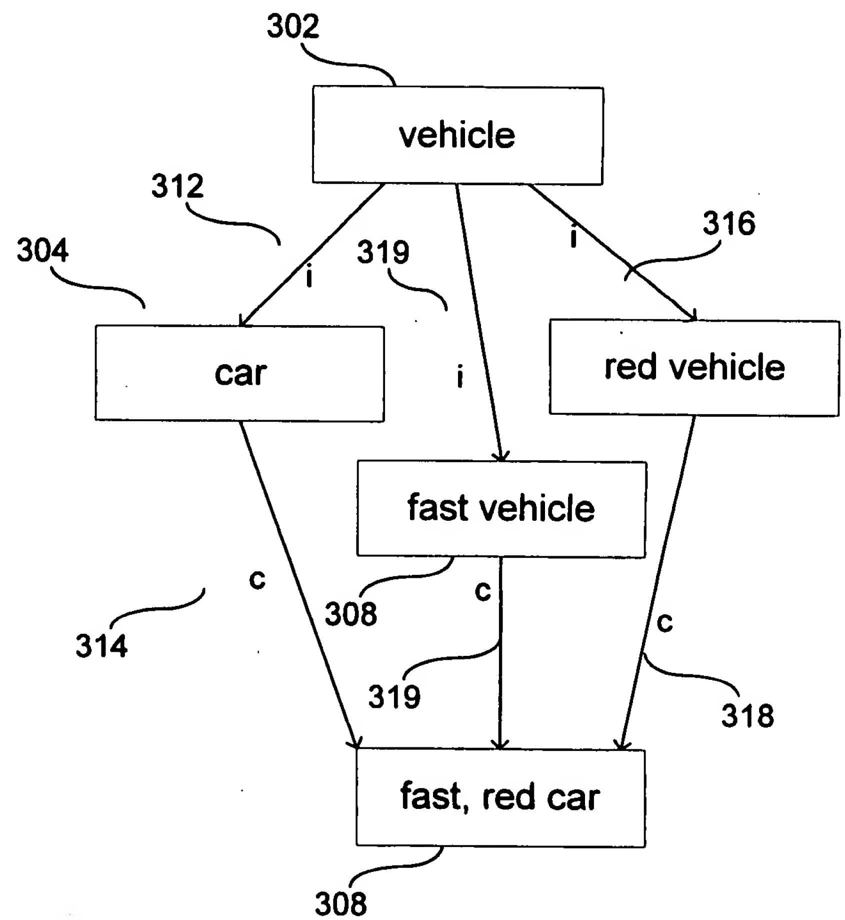
Refining a Specification
Fig. 3(a)



Example of Using a Colimit to
Combine Refined Specifications
Fig. 3(b)

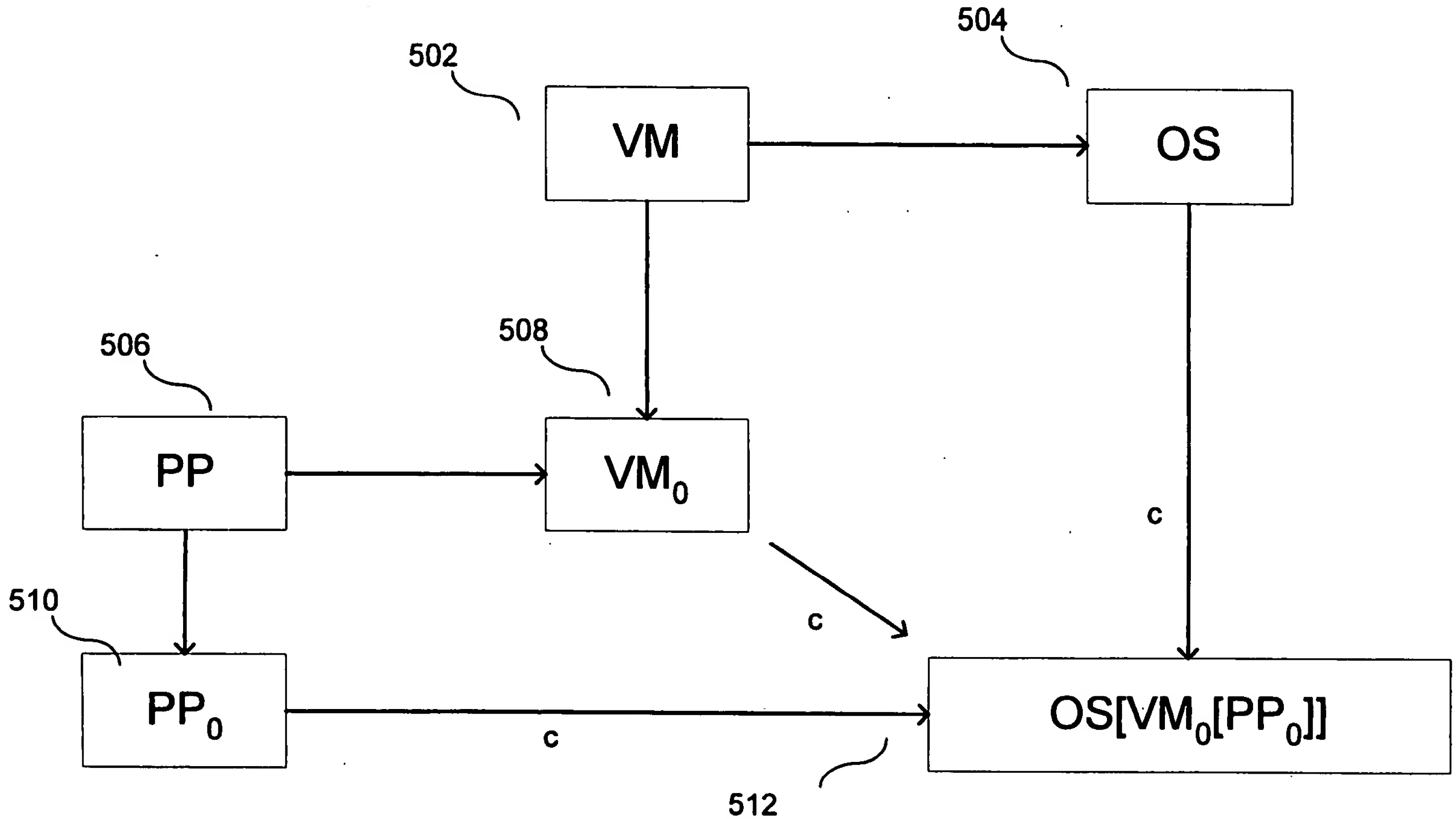


Refining a Specification
Fig. 4(a)

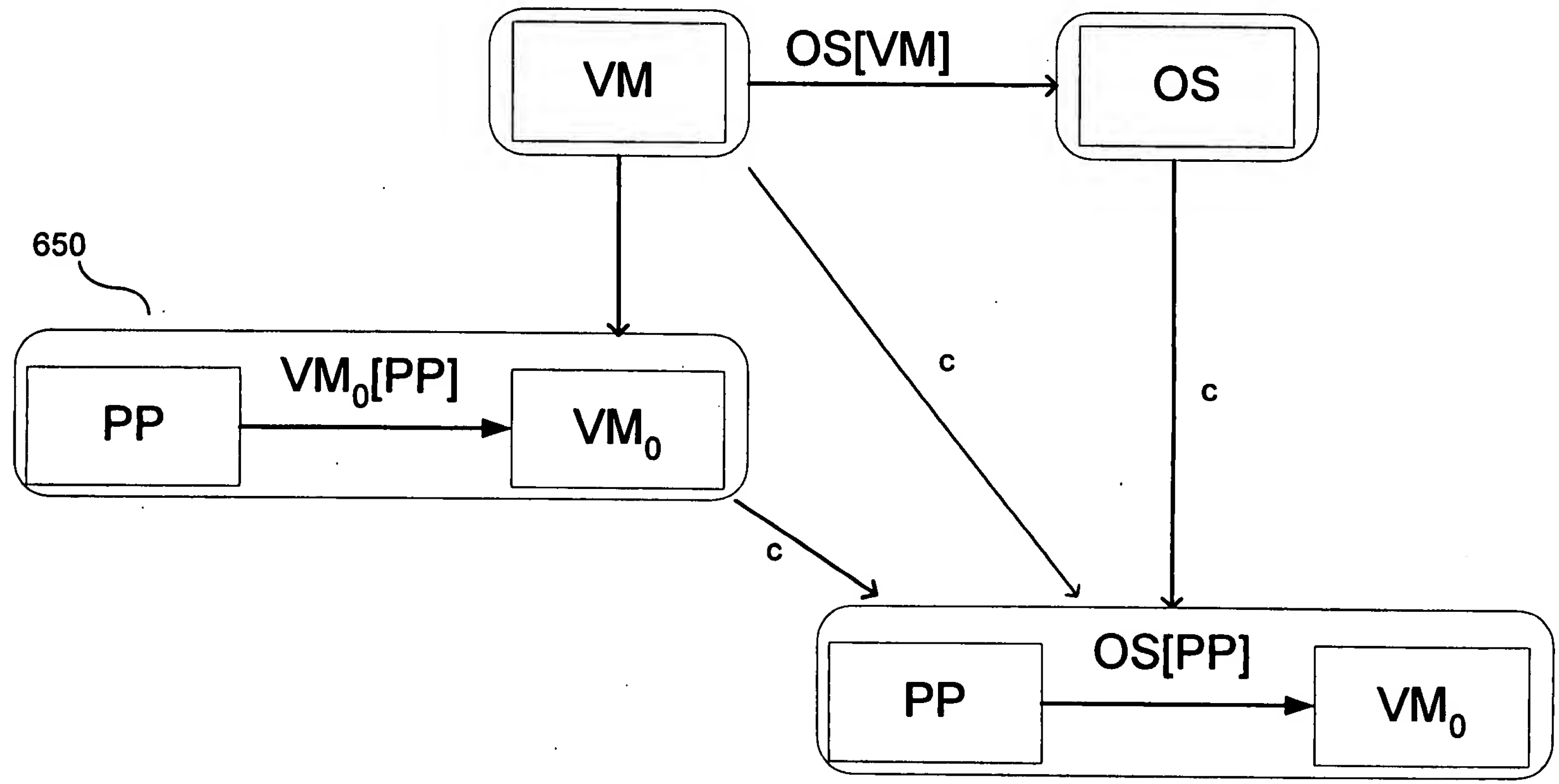


Example of Using a Colimit to
Combine Refined Specifications
Fig. 4(b)

0965172.091903

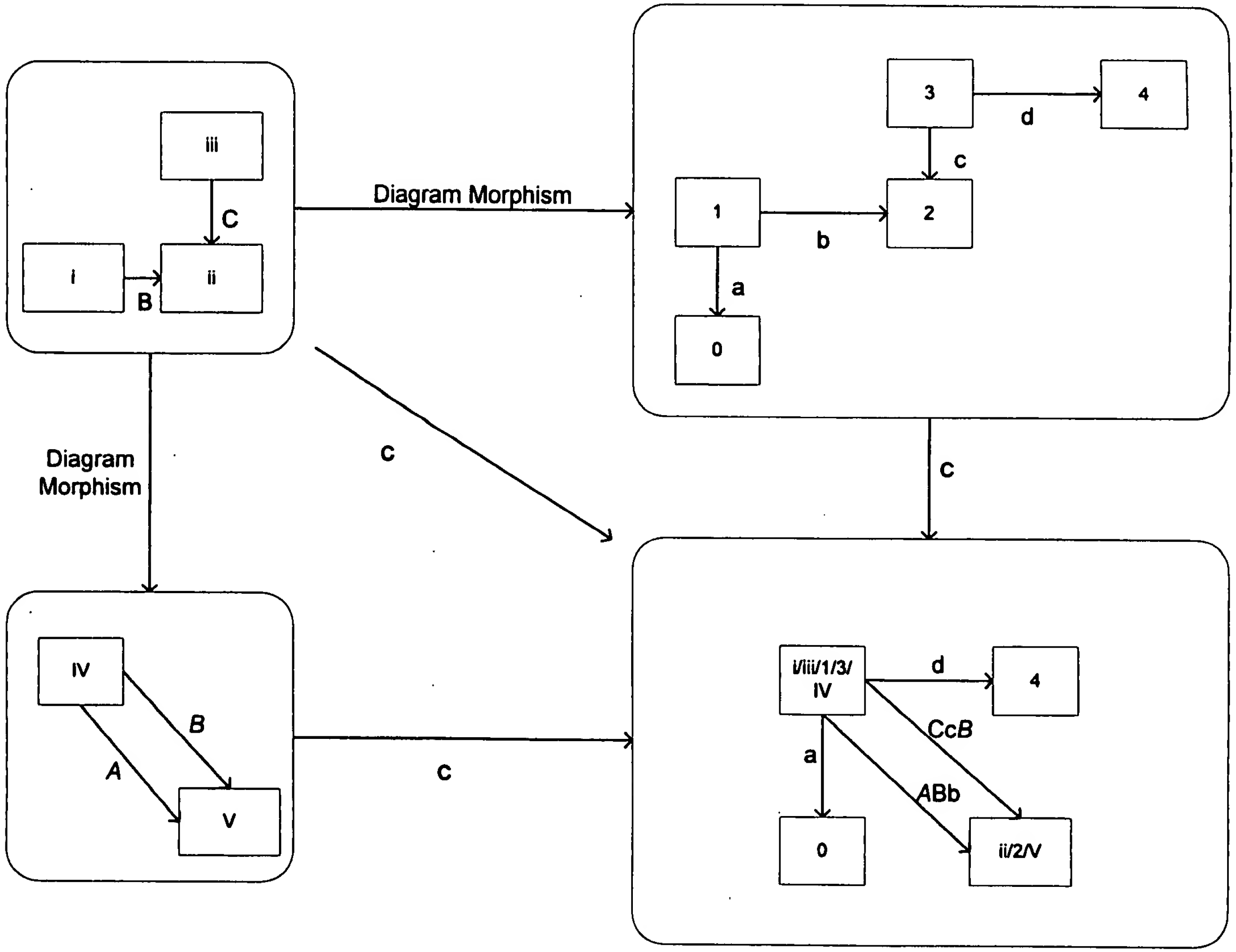


Example Colimit of Specifications
Fig. 5

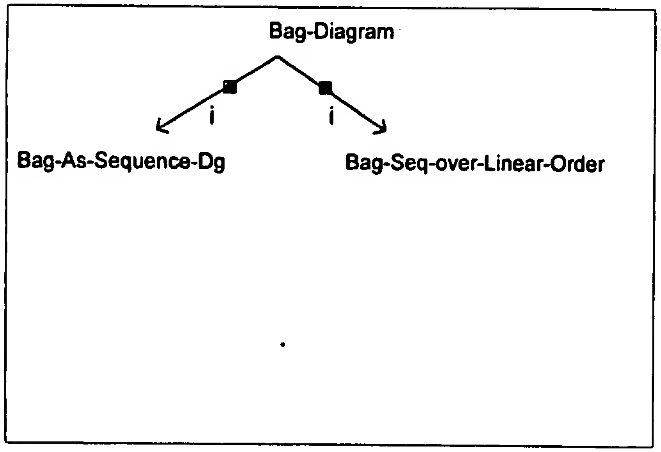


Example Colimit of Diagrams of Diagrams

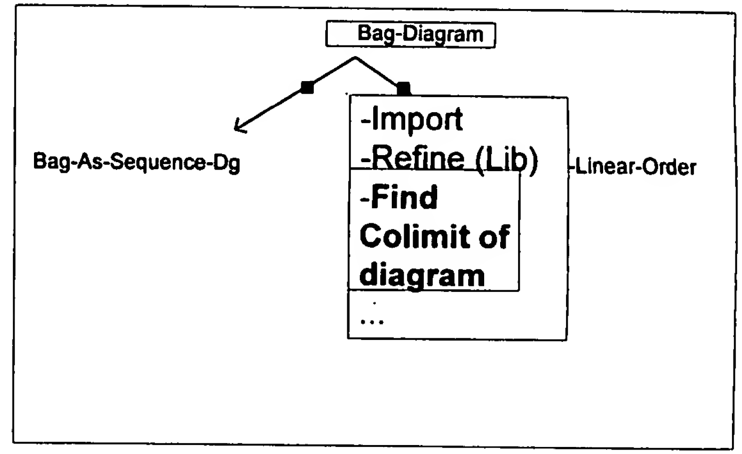
Fig. 6



Example of Taking the Colimit of Hereditary Diagrams
Fig. 7

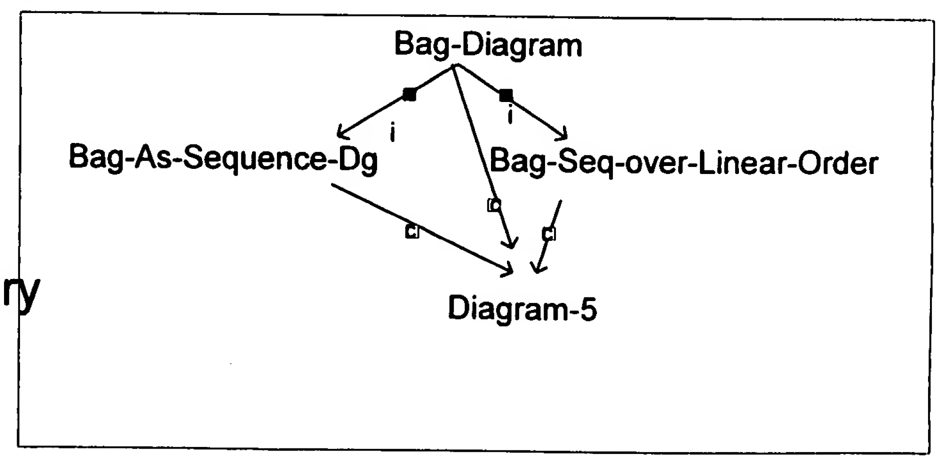


Example user interface showing a hereditary diagram
Fig. 8(a)

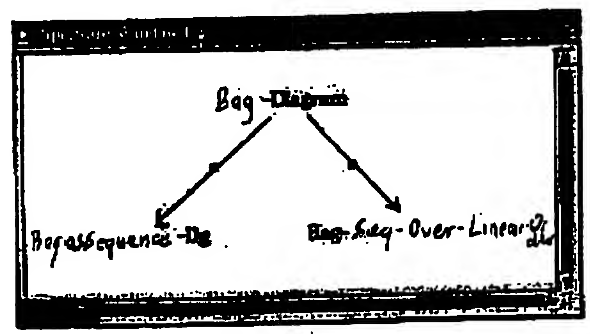


Example user interface showing a hereditary diagram (interface for user to indicate "find colimit" operation)
Fig. 8(b)

Example user interface showing a hereditary diagram after the user indicates a "find colimit" operation for the hereditary diagram and the colimit operation is performed
Fig. 8(c)

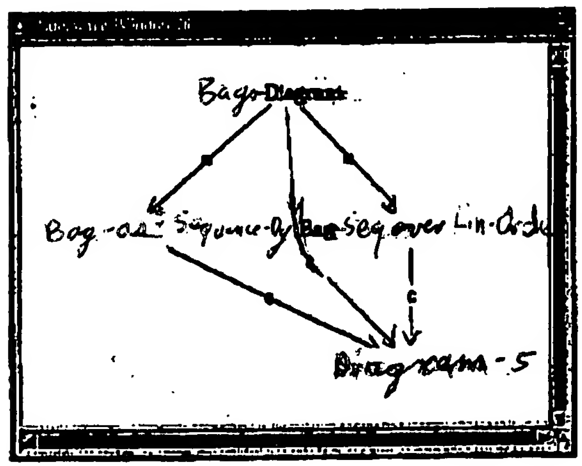


09655172.094900



Hereditary diagram
Fig 9(a)

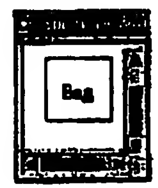
09665177.091900



Hereditarydiagram, including colimit

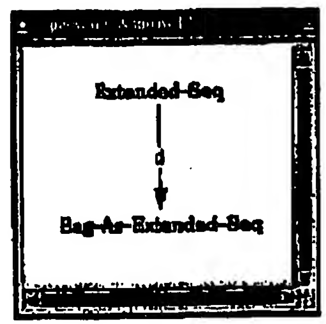
Fig 9(b)

09665179.091900



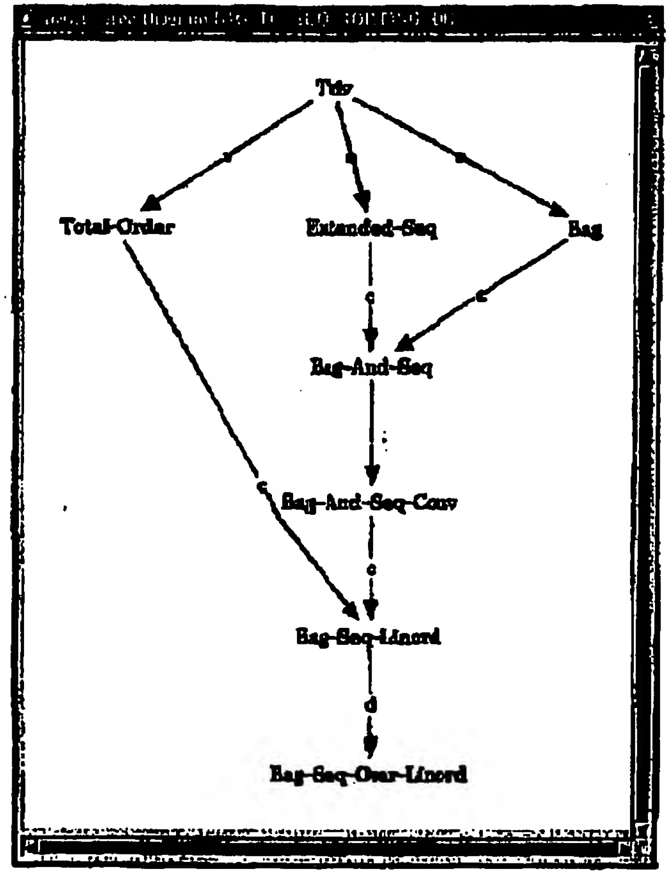
Bag diagram
(obtained by expanding node
Bag-Diagram
in Hereditary diagram)

Fig 4(c)



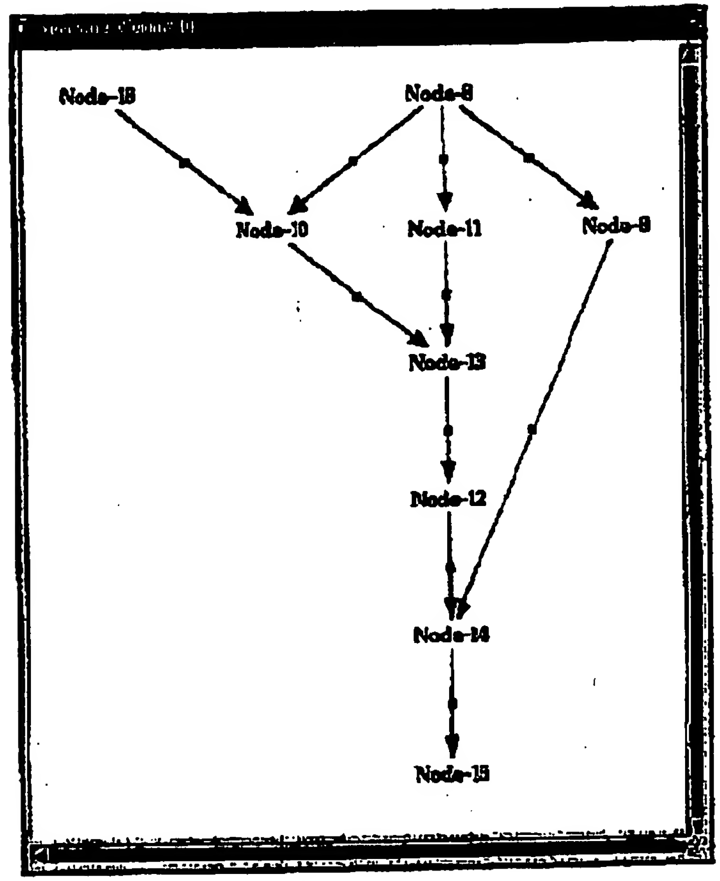
Bag-as-Sequence diagram
(obtained by expanding node
Bag-as-Sequence-diagram
In Hereditary diagram)

Fig 9(d)

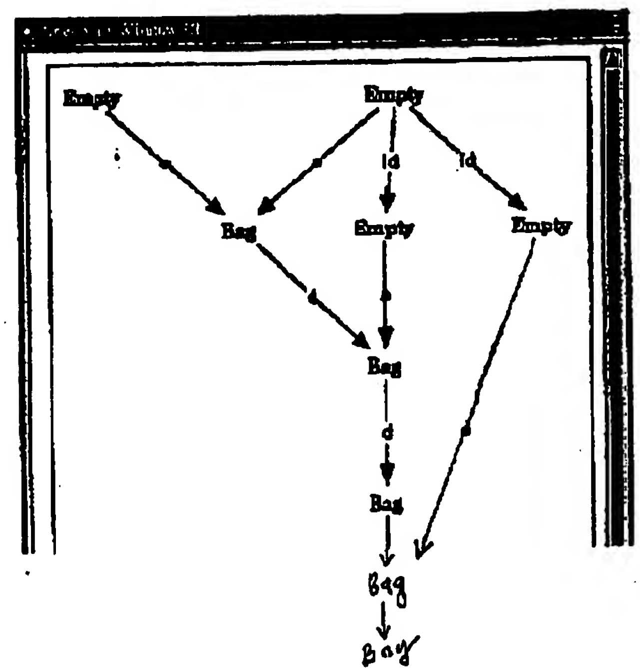


Bag-Seq-over-Linear-Order diagram
(obtained by expanding node
Bag-Seq-over-Linear-Order-diagram
in Hereditary diagram)

Fig 9(e)

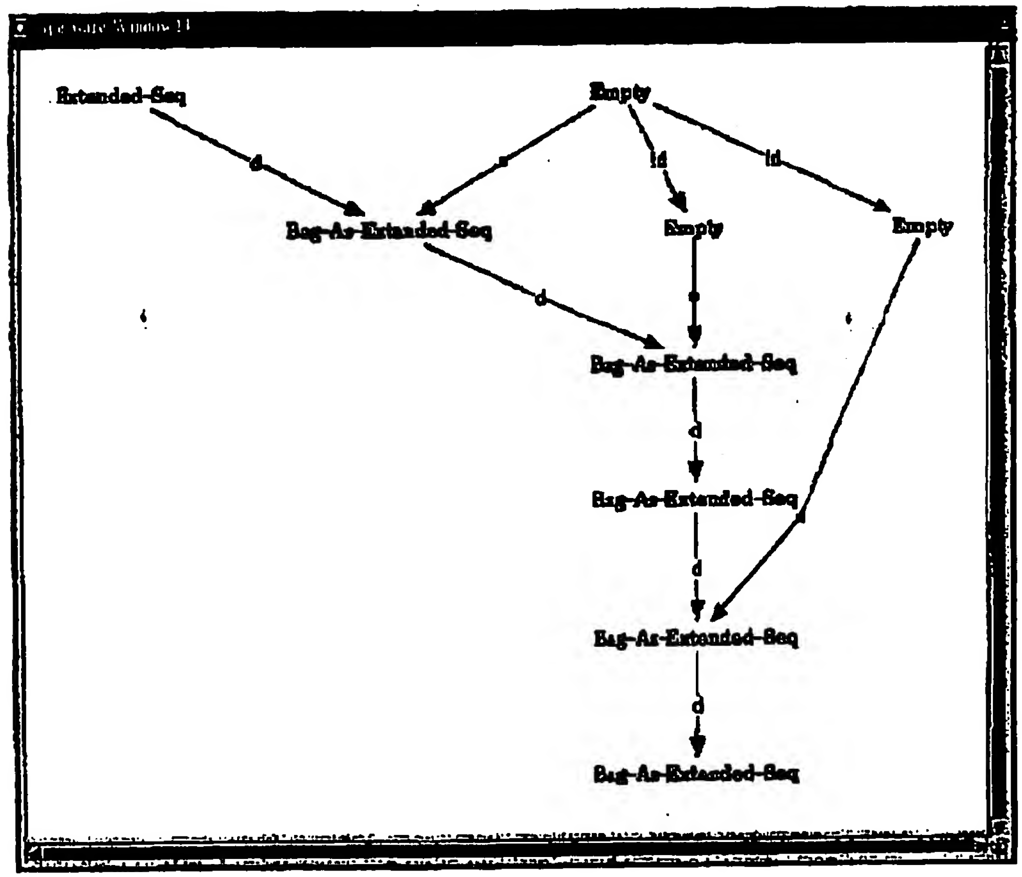


Shape of colimit
Fig 9(f)



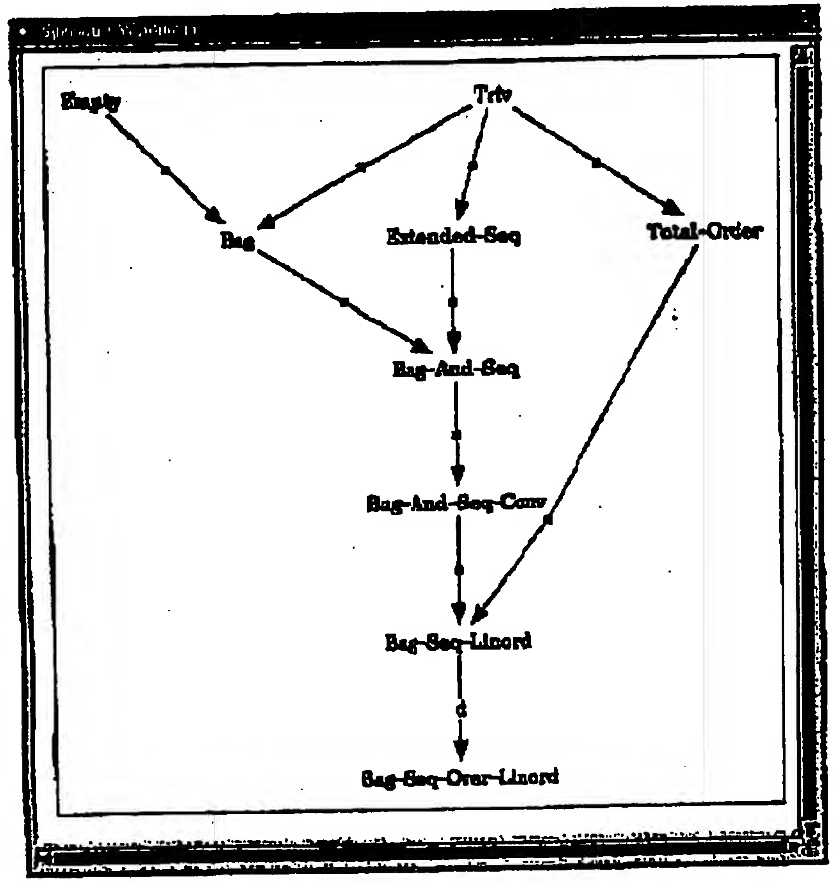
Extended Bag diagram

Fig. 9(g)



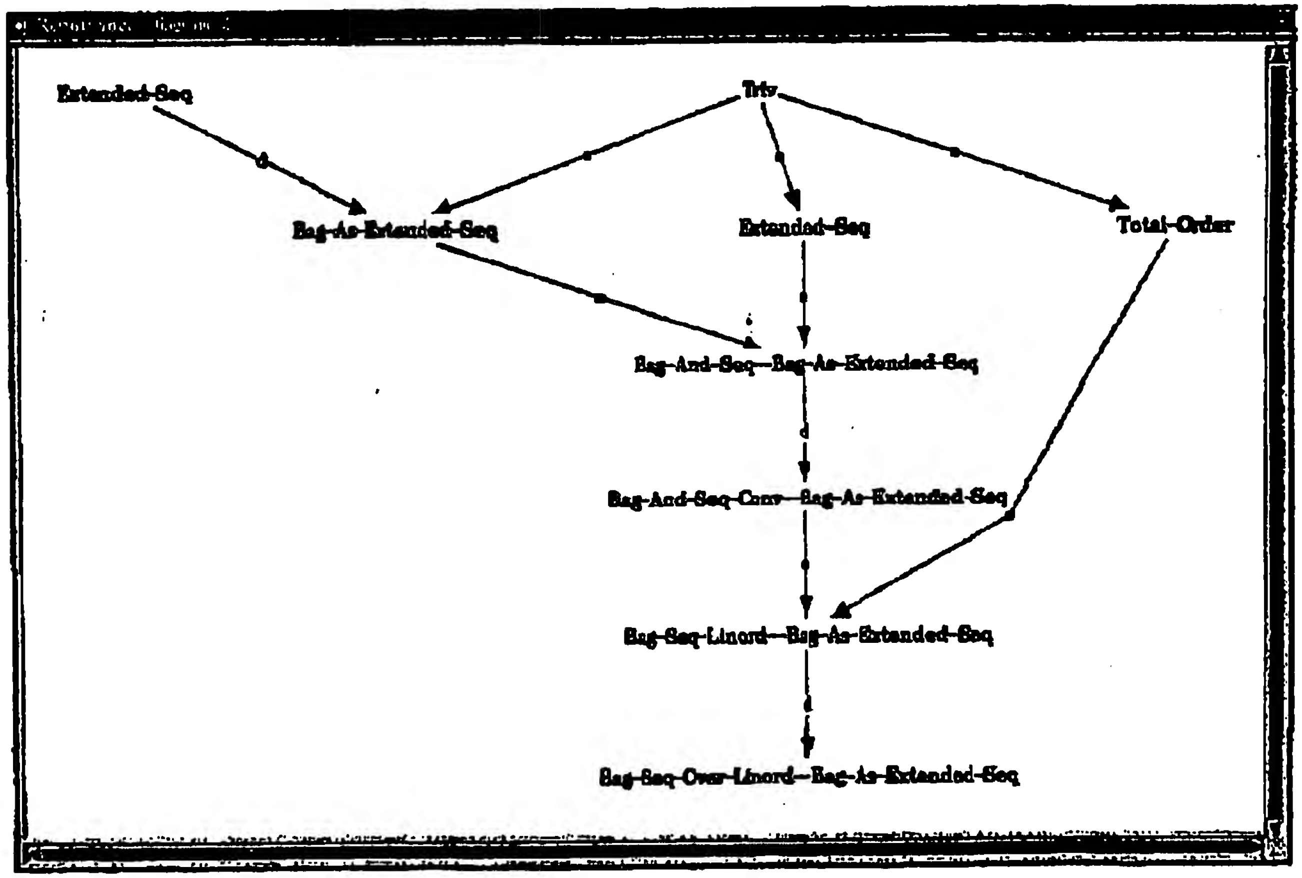
Extended Bag-as-Sequence diagram

Fig 9(h)



Extended Bag-Seq-over-Linear-Order diagram

Fig 9(i)



Colimit of Hereditary diagrams
(final result)
Fig 9(j)

1002 — User wants to take the colimit of a hereditary diagram (see Fig. 8(b))

↓

I

1004 — From the hereditary diagram, extract the shapes of its nodes and the functors between them to yield a diagram of shape categories. (see Fig. 11) Determine the colimit of the diagram of shape categories. The colimit of shape categories has the same shape as the colimit of diagrams that we are trying to determine (see Fig. 16)

↓

II

1006 — For each diagram of the hereditary diagram, determine its extension in accordance with the colimit shape obtained in the previous step. (This brings each of the diagrams to the same shape) (see Fig. 19)

↓

III

1008 — Take pointwise colimit of the extended diagrams to yield the desired colimit of the hereditary diagram. The morphisms of the colimit are uniquely determined by the universality of the pointwise colimits (Can take the pointwise colimit because the extended diagrams are all of the same shape) (See Fig. 22)

↓

1010 — Store newly determined colimit in a memory. Add name of newly determined colimit to display (User can view details of colimit if he wishes) (see Fig. 9)

Finding a Colimit of Hereditary Diagrams

Fig. 10

for each diagram/
node in the
hereditary diagram
(3 in this example)

Store in memory a set of the arcs in the diagram,
i.e., arc_set := arcs in diagram

↓

Store in memory a set of the nodes in the diagram,
i.e., node_set := nodes in diagram

↓

For each element in the set of arcs, associate with the arc (in memory) a source node (S) and a target node (T) in accordance with the connections of the diagram

↓

Determine the morphisms (F_e) between the arcs of each source diagram and the arcs of each target diagram

↓

Determine the morphisms (F_n) between the nodes of each source diagram and the nodes of each target diagram

PART I: Extract the shapes and shape functors to yield a diagram of shape categories

Fig. 11

$$
\begin{tikzcd}
d1 \arrow[r, Rightarrow, "a1"] \arrow[d, Rightarrow, "a2"'] & d2 \\
d3 &
\end{tikzcd}
$$

A Hereditary Diagram: Three Diagrams and Two Arcs.

Each arc a1 and a2 represents a shape morphism having 1) a shape functor (such as F) and 2) a natural shape transformation (such as e: d1 --> d2)

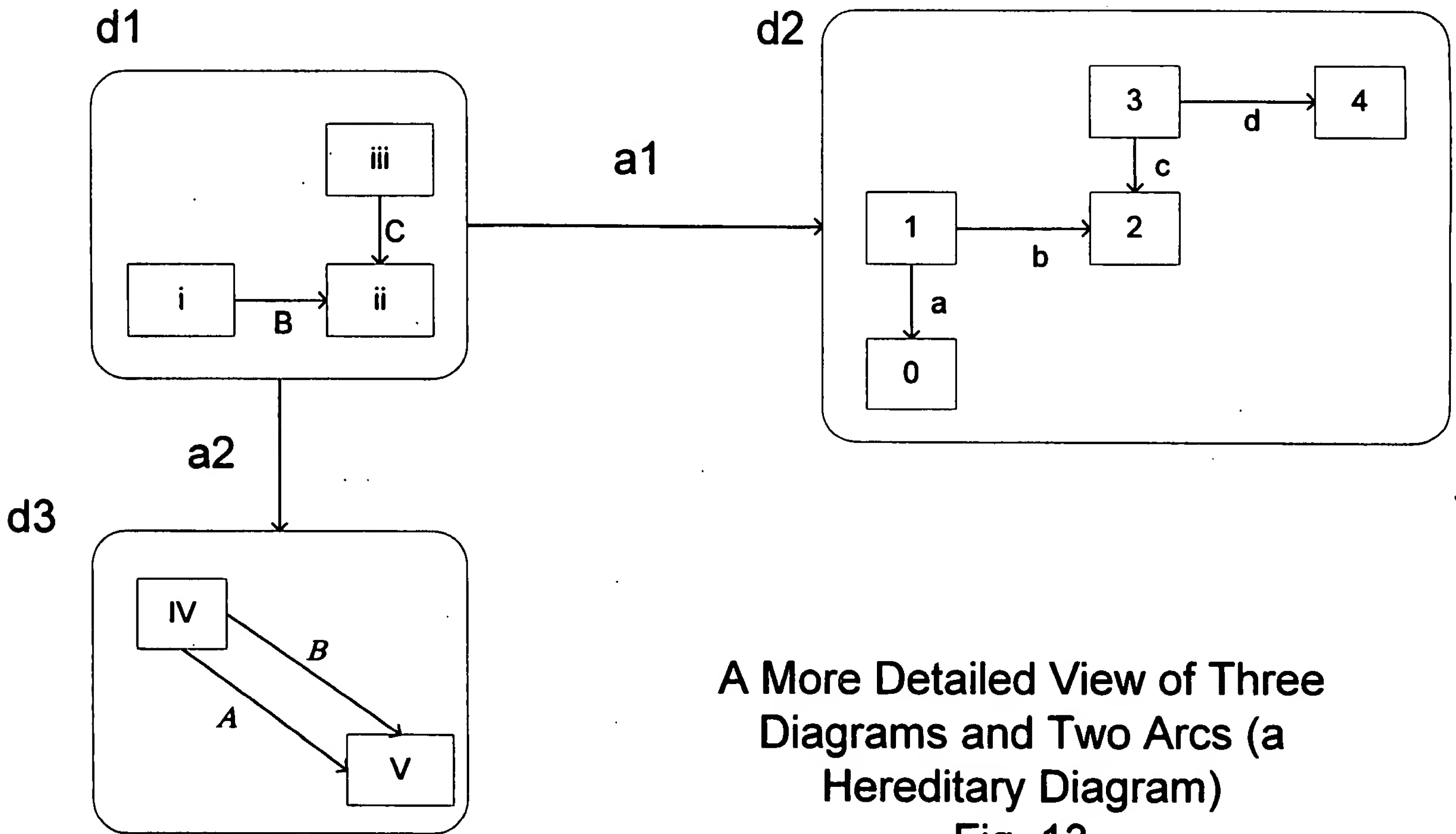
Fig. 12(a)

$$
\begin{tikzcd}
D1 \arrow[rr, dashed, "F"] \arrow[dr, dashed, "d1"'{name=L}] & & D2 \arrow[dl, dashed, "d2"{name=R}] \\
& SPEC &
\arrow[from=L, to=R, Rightarrow, "e"]
\end{tikzcd}
$$

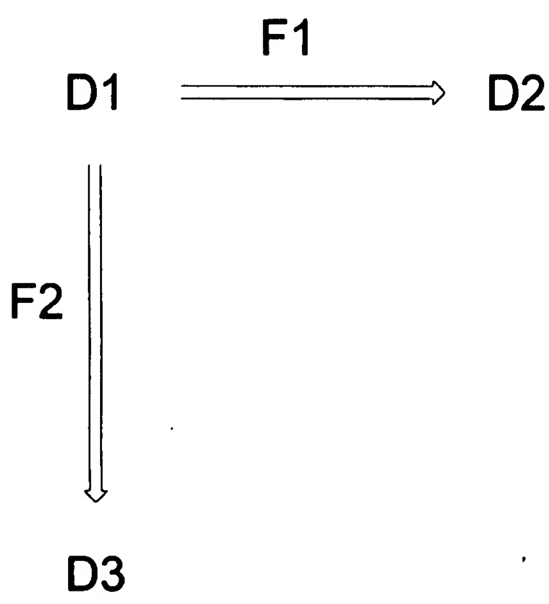
A Shape Morphism

where d1 and d2 are diagrams,
F is a shape functor,
e is a natural transformation from d1 to (d2 composed with F)
D1 and D2 are shape categories of diagrams, and SPEC is the category Spec

Fig. 12(b)

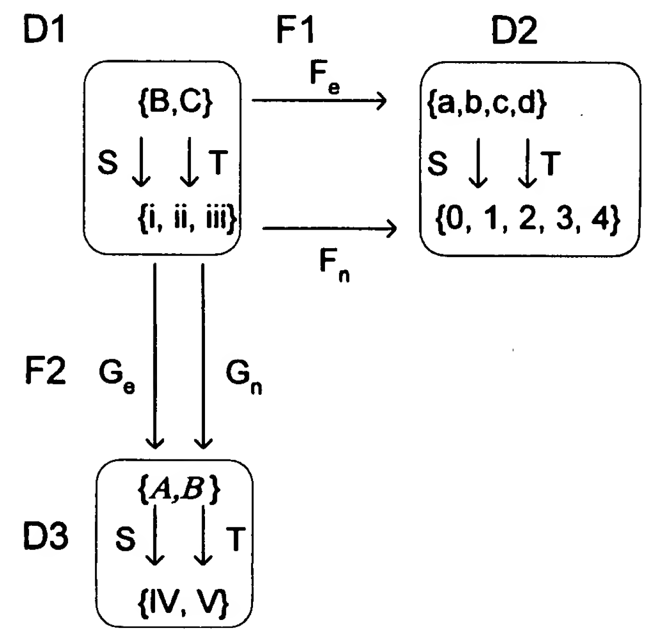


A More Detailed View of Three Diagrams and Two Arcs (a Hereditary Diagram)
Fig. 13



Extract the Shapes and Shape Functors (D1 is shape of diagram d1, F1 is shape functor)

Fig. 14



More Detailed View of Extracting the Shapes and Shape Functors (continued on Figs. 15(b)-15(d))

Fig. 15(a)

Arcs: B -> b
C -> c
Nodes: i -> 1
ii -> 2
iii -> 3

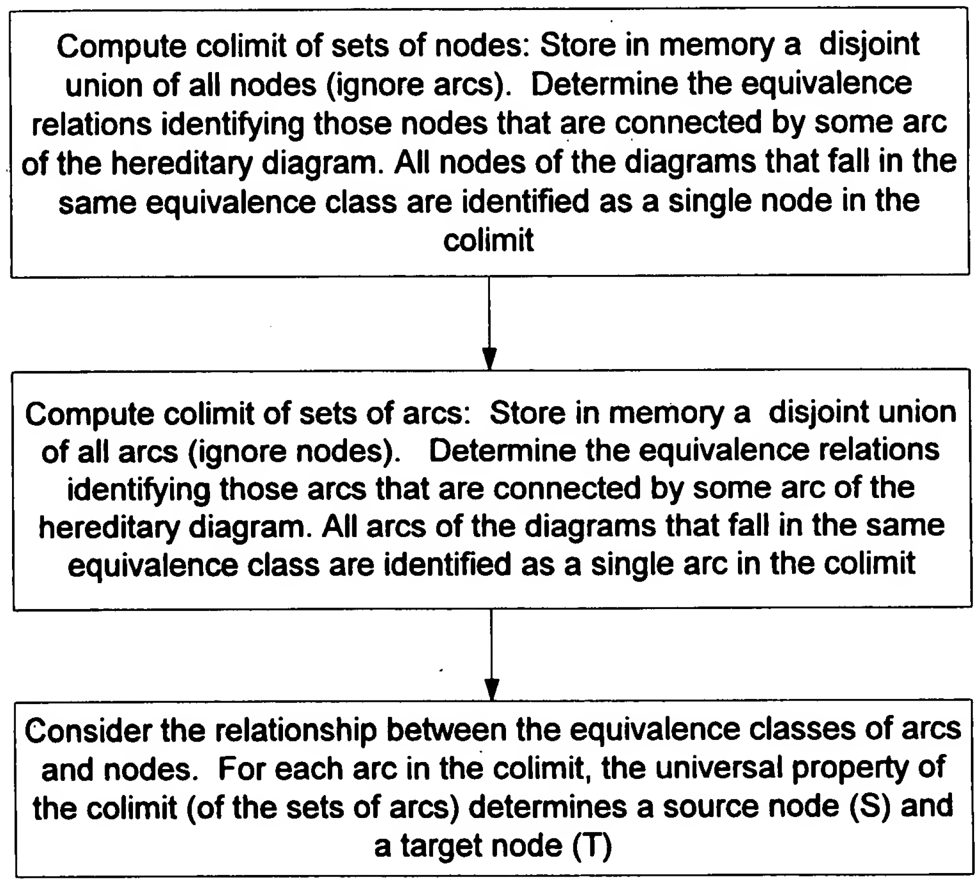
Mapping for F1
Fig. 15(b)

Arcs: B -> *A*
C -> *B*
Nodes: i -> IV
ii -> V
iii -> IV

Mapping for F2
Fig. 15(c)

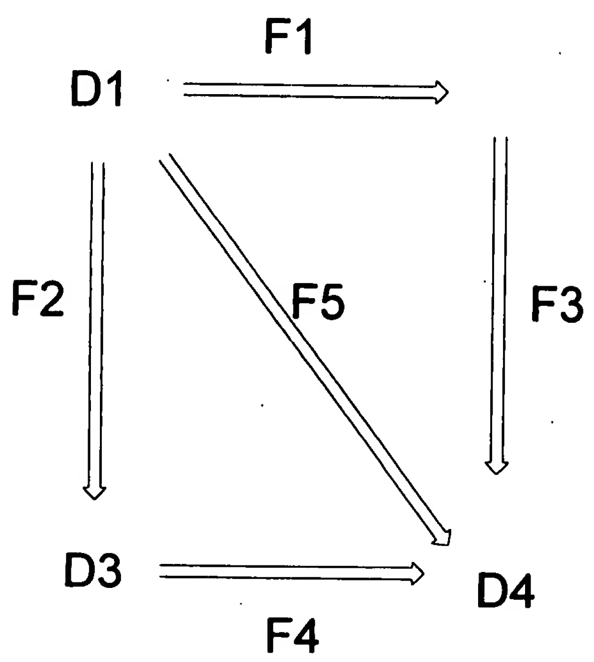
Arc	B	C	a	b	c	d	*A*	*B*
Source	i	iii	1	1	3	3	IV	IV
Target	ii	ii	0	2	2	4	V	V

Source (S) and Target (T) Functions for Hereditary Diagrams
Fig. 15(d)

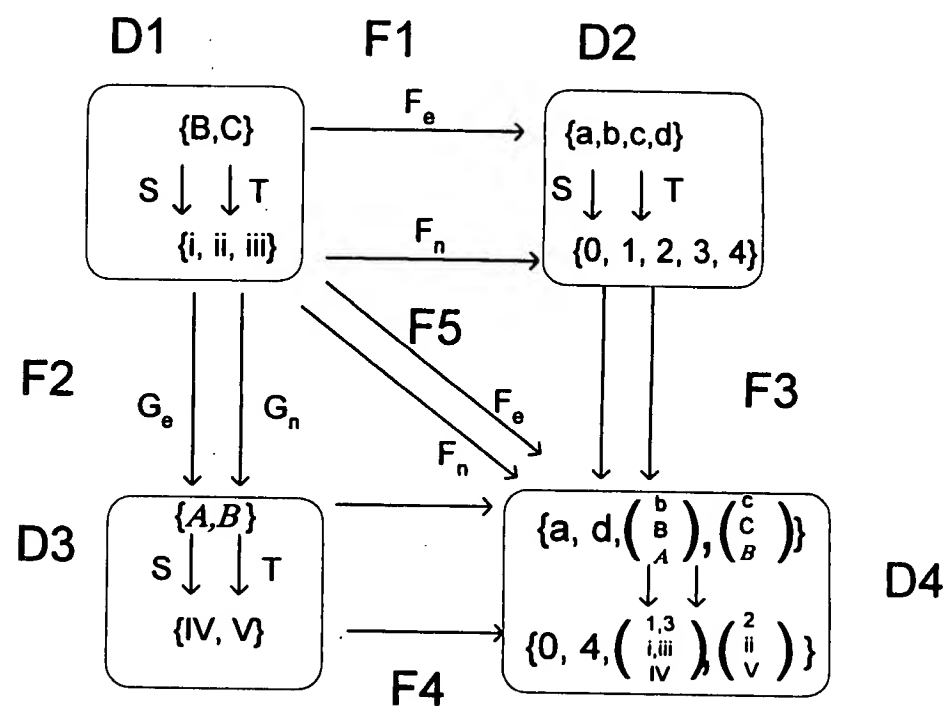


PART I: Determine the colimit of the diagram of shape categories.

Fig. 16



More Detailed View of Taking the Colimit
Fig. 17

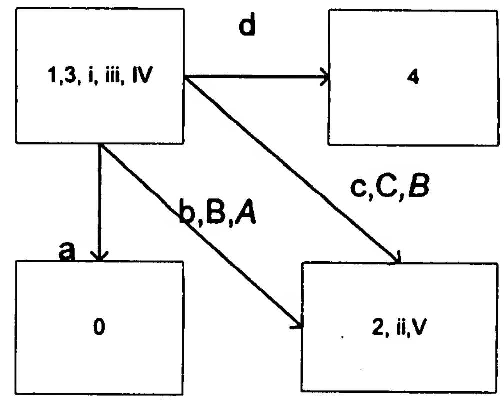


More Detailed View of Taking the Colimit
(See Figs 18(b)-(f))

Fig. 18(a)

Arc	a	d	b A *A*	c C *B*
Source	1,3 i,iii IV	1,3 i,iii IV	1,3 i,iii IV	1,3 i,iii IV
Target	0	4	2 ii V	2 ii V

Source (S) and Target (T) Functions for Shape Colimit D4
Fig. 18(b)



The Colimit D4 of the Shape Diagrams
Fig. 18(c)

Arcs: a -> a
d -> d
b -> b,B,*A*
c -> c,C,*B*

Nodes: 0 -> 0
1 -> 1,3, i,iii, IV
2 -> 2, ii,V
3 -> 1,3, i,iii, IV
4 -> 4

Mapping for F3
Fig. 18(d)

Arcs: *A* -> b,B,*A*
B -> c,C,*B*

Nodes: IV -> 1,3, i, iii, IV
V -> 2, ii,V

Mapping for F4
Fig. 18(e)

Arcs: B -> b,B,*A*
C -> c,C,*B*

Nodes: i -> 1,3, i, iii, IV
ii -> 2, ii,V
iii -> 1,3, i, iii, IV

Mapping for F5
Fig. 18(f)

0955179.091900

For each node n in colimit D4:

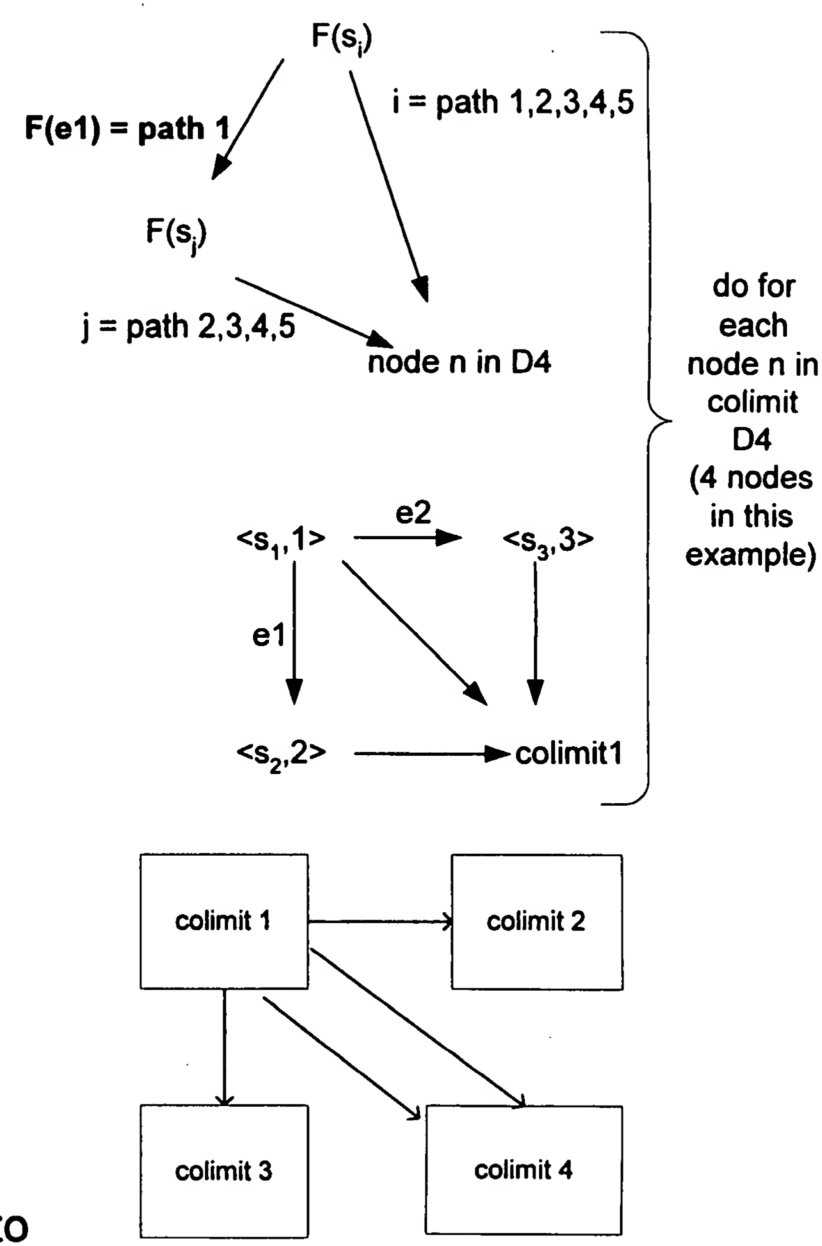
Find nodes s in shape diagram (for example diagram D1) that have a path i to the node n. Yields a set of pairs : {<s,i> | i is a path from F(s) to node n in D4}

For two pairs in the set (for example: $<s_i,i>$ and $<s_j,j>$)

By definition, s_i and s_j both connect to the same node in colimit D4. Find a path e between s_i and s_j

Once each path F(e) has been found between each pair in the set, make a graph and take the colimit. This colimit is the image of node n in the extended diagram

Each arc in D4 is uniquely defined and determined using the universality of the colimits for the nodes in the extended diagram



extended diagram from example

PART II:Extending one Diagram (repeat to extend each diagram)

Fig. 19

09665179.091900

<u>Extension for Diagram d1:</u>

$$\begin{tikzcd} D1 \arrow[rr] \arrow[dr, Rightarrow, "F5"'] & & SPEC \\ & D4 \arrow[ur, Rightarrow, "Lf\,5d1"'] & \end{tikzcd}$$

<u>Extension for Diagram d2:</u>

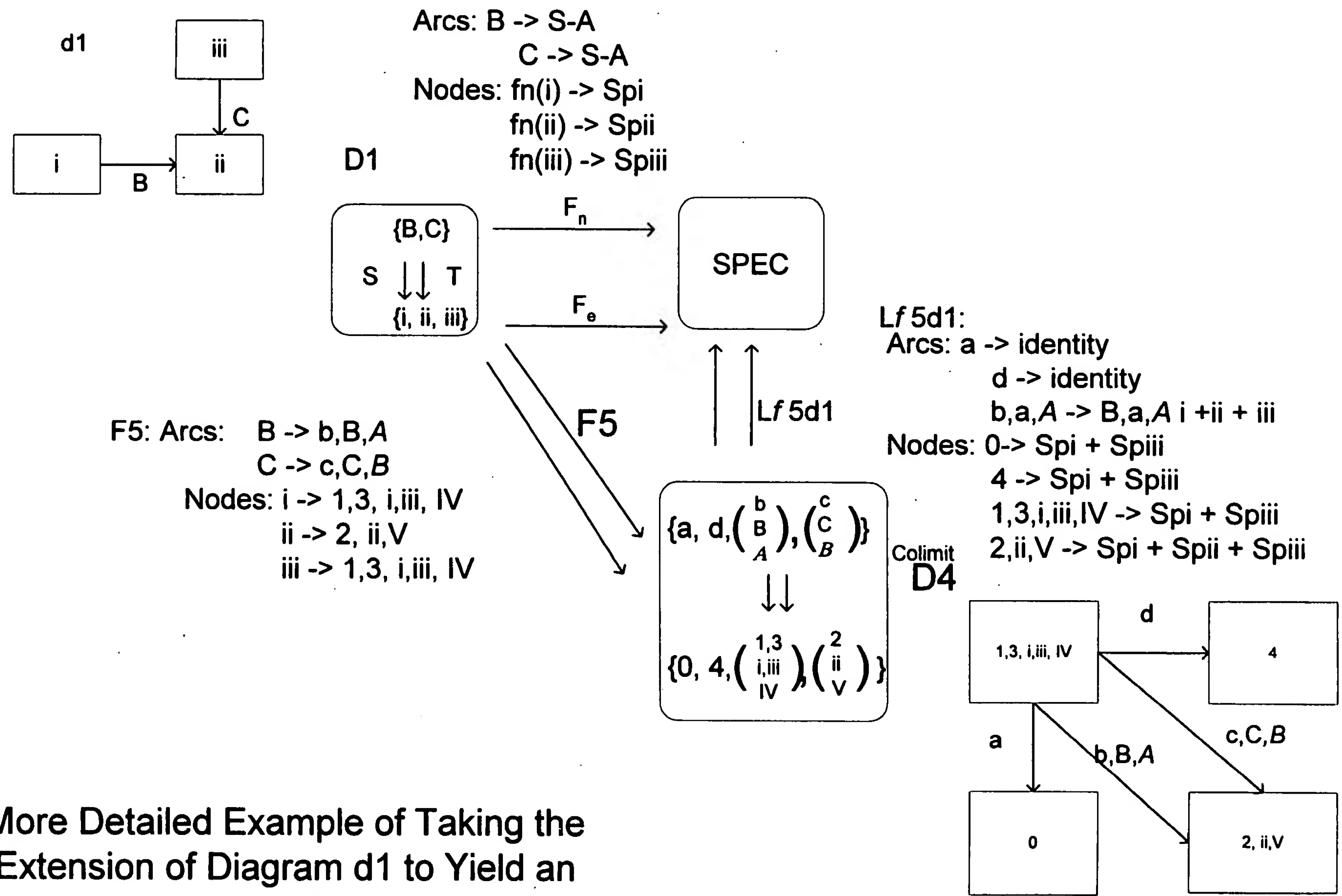
$$\begin{tikzcd} D2 \arrow[rr] \arrow[dr, Rightarrow, "F3"'] & & SPEC \\ & D4 \arrow[ur, Rightarrow, "Lf\,3d2"'] & \end{tikzcd}$$

<u>Extension for Diagram d3:</u>

$$\begin{tikzcd} D3 \arrow[rr] \arrow[dr, Rightarrow, "F4"'] & & SPEC \\ & D4 \arrow[ur, Rightarrow, "Lf\,4d3"'] & \end{tikzcd}$$

Example of Taking the Extension of Each Node of the Hereditary Diagram

Fig 20



More Detailed Example of Taking the Extension of Diagram d1 to Yield an Extended Diagram

Fig. 21(a)

$i \xrightarrow{F_5} \begin{pmatrix} 1,3 \\ i, iii \\ \mathrm{IV} \end{pmatrix} \downarrow a$ Node 0

$\left\{ \langle i, a \rangle \;\middle|\; a : F_5(i) = \begin{pmatrix} 1,3 \\ i, iii \\ \mathrm{IV} \end{pmatrix} \xrightarrow{a} 0 \right\}$

$\left\{ \langle iii, a \rangle \;\middle|\; a : F(iii) = \begin{pmatrix} 1,3 \\ i, iii \\ \mathrm{IV} \end{pmatrix} \xrightarrow{a} 0 \right\}$

1

For four Nodes in D4

$\langle i, a \rangle \rightarrow 0$, id, $\langle iii, a \rangle \rightarrow 0$

$\langle i, a \rangle \longrightarrow Sp_i$ $+$ $\langle iii, a \rangle \longrightarrow Sp_{iii}$ coproduct (i.e. no arc between the...)

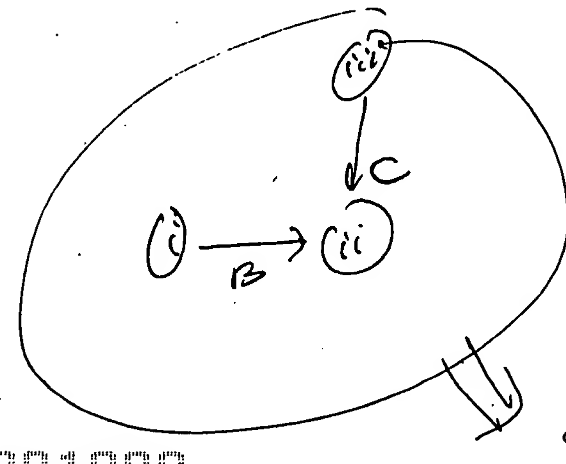
Node 4

$\left\{ \langle i, d \rangle \;\middle|\; d : F_5(i) = \begin{pmatrix} 1,3 \\ i, iii \\ \mathrm{IV} \end{pmatrix} \xrightarrow{d} 4 \right\}$

$\left\{ \langle iii, d \rangle \;\middle|\; \text{———} \quad \text{———} \right\}$ same as above

Node $\begin{pmatrix} 1,3 \\ i, iii \\ \mathrm{IV} \end{pmatrix}$ $\left\{ \begin{matrix} \langle i, id \rangle \\ \langle iii, id \rangle \end{matrix} \right\}$

Node $\begin{pmatrix} 2 \\ ii \\ \mathrm{V} \end{pmatrix}$ $\left\{ \begin{matrix} (i, BA) \\ (iii, CB) \\ (ii, id) \end{matrix} \right\}$



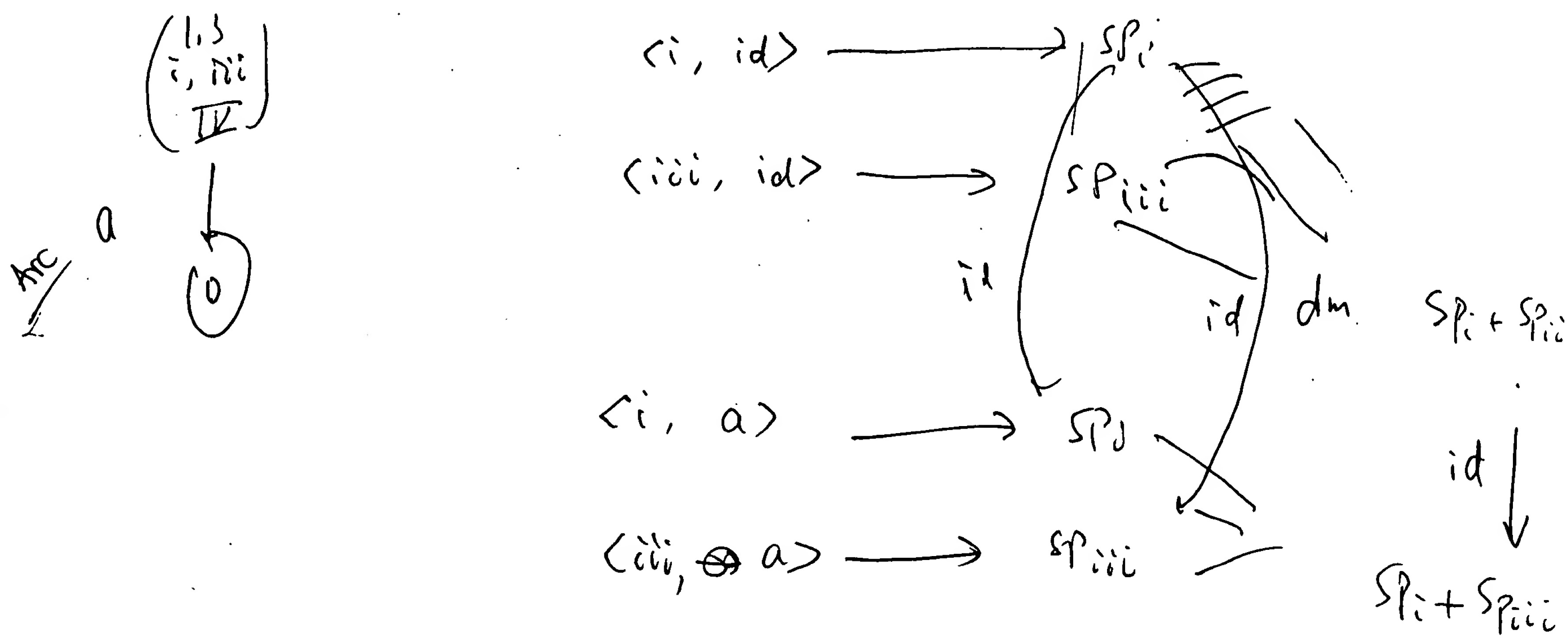
$Sp_{i+ii+iii}$ colimit

Fig 21(b) Example of Diagram Extension

0065479.001900

Fig 15 (2)

for arcs in D4



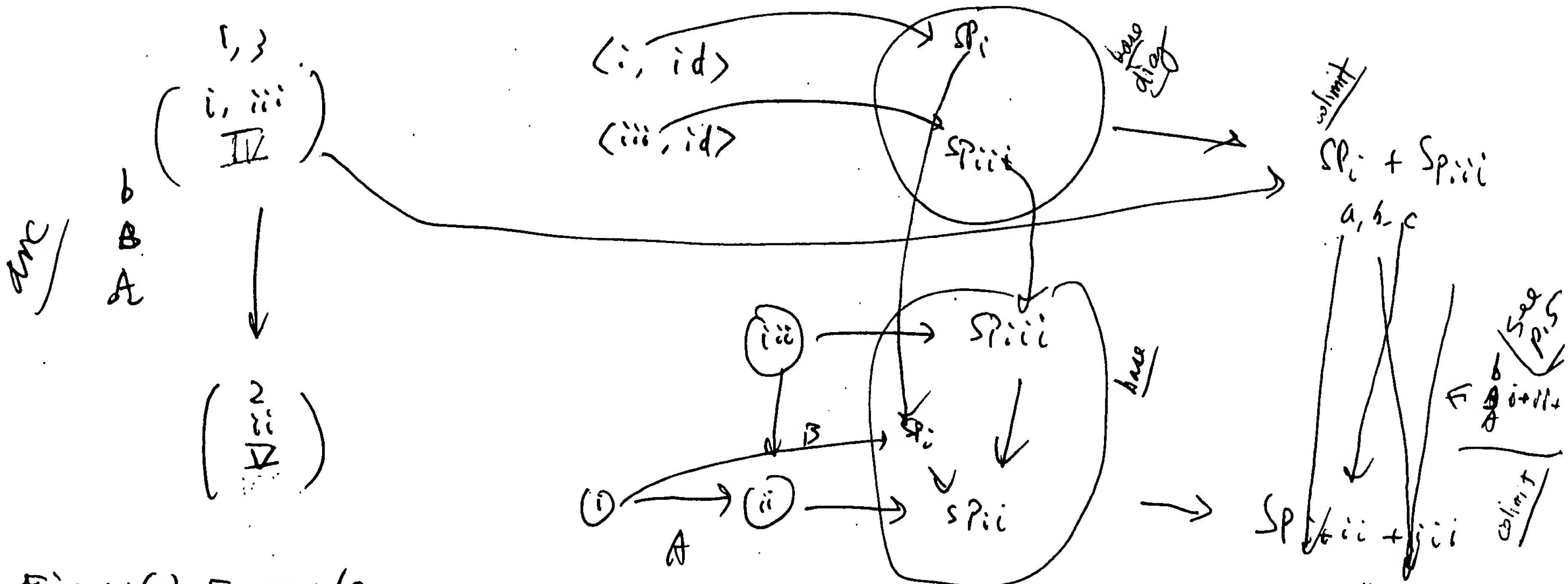
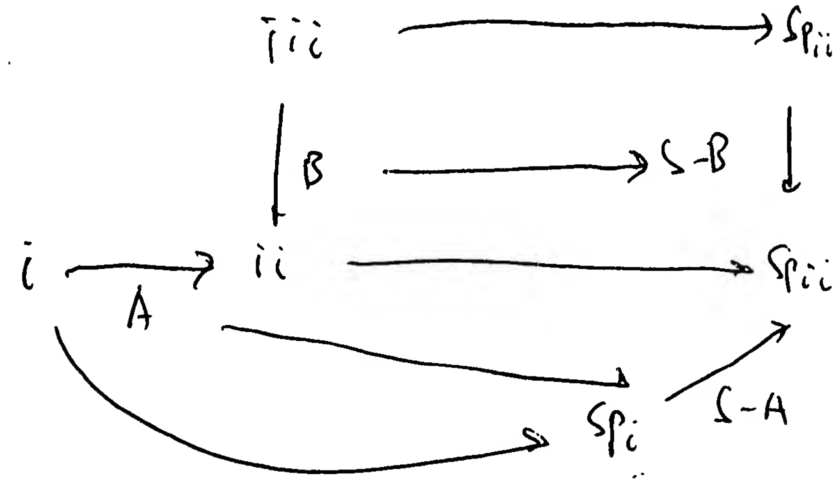


Fig 21(c) Example of Diagram extension (cont) 09655179.091900

(J)

$$Sp_i = \left\{ \begin{array}{l} \text{spec } Sp_i \text{ is} \\ \quad \text{sort } S_1 \\ \quad \text{op } f_1 : S_1 \to \text{boolean} \\ \quad \text{op } f_2 : S_1 \to \text{boolean} \\ \quad \text{axiom } f_1 \to f_2 \text{ is} \\ \qquad f_1(x) \Rightarrow f_2(x) \end{array} \right\}$$



Base diagram

$$Sp_{ii} = \left\{ \begin{array}{l} \text{spec } Sp_{ii} \text{ is} \\ \quad \text{sort } S_2 \\ \quad \text{op } g : S_2 \to \text{boolean} \end{array} \right\}$$

$$Sp_{iii} = \left\{ \begin{array}{l} \text{spec } Sp_{iii} \text{ is} \\ \quad \text{sort } S_1 \\ \quad \text{op } f_1 : S_1 \to \text{boolean} \end{array} \right\}$$

$$S\text{-}A = \left\{ \begin{array}{lcl} Sp_i & \longrightarrow & Sp_{ii} \\ S_1 & \longrightarrow & S_2 \\ f_1 & \longrightarrow & g \\ f_2 & \longrightarrow & g \end{array} \right\} \qquad S\text{-}B = \left\{ \begin{array}{lcl} Sp_{iii} & \longrightarrow & Sp_{ii} \\ S_1 & \longrightarrow & S_2 \\ f_1 & \longrightarrow & g \end{array} \right\}$$

Fig 21(d) Example of diagram (cont)

(c)

$$\begin{tikzcd}
 & Sp_{iii} \arrow[d, "S-B"] \arrow[ddr, bend left, "C_{iii}"] & \\
Sp_i \arrow[r, "S-A"] \arrow[drr, "C_i"'] & Sp_{ii} \arrow[dr, "C_{ii}"] & \\
 & & Sp_{i+ii+iii}
\end{tikzcd}$$

$C_i = \left(\begin{array}{l} Sp_i \longrightarrow Sp_{i+ii+iii} \\ S_1 \longrightarrow S_2 \\ f_1 \longrightarrow g \\ f_2 \longrightarrow g \end{array} \right)$

$C_{ii} = \left(\quad id \quad \right)$

$C_{iii} = S-B$

colimit

$Sp_{i+ii+iii} = \left\{ \begin{array}{l} \text{spec } Sp_{i+ii+iii} \text{ is} \\ \text{sort } \boxed{\begin{array}{ll} \text{sort} & Sp_i . S_1 \\ \text{sort} & Sp_{iii} . S_1 \\ \text{sort} & S_2 \end{array}} \quad S_2 \\ \text{op } g : S_2 \rightarrow \text{boolean} \\ \text{axiom } g\text{-}g \text{ is} \\ \quad g(x) \Rightarrow g(x) \end{array} \right\}$

Fig 21(e) Example of Diagram Extension (cont)

$$Sp_i + Sp_{iii} = \left\{ \begin{array}{l} \text{sort } Sp_i \cdot S_1 \\ \text{sort } Sp_{iii} \cdot S_1 \\ \text{op } Sp_i \cdot f_1 : Sp_i \cdot S_1 \to \text{boolean} \\ \text{op } Sp_{iii} \cdot f_1 : Sp_{iii} \cdot S_1 \to \text{boolean} \\ \text{op } Sp_i \cdot f_2 : Sp_i \cdot S_1 \to \text{boolean} \end{array} \right.$$

$$\Big\downarrow \; {}^{b}_{A}\, i+ii+iii$$

$$Sp_{i+ii+iii} = \left\{ \quad \text{See 21(?)} \quad \right\}$$

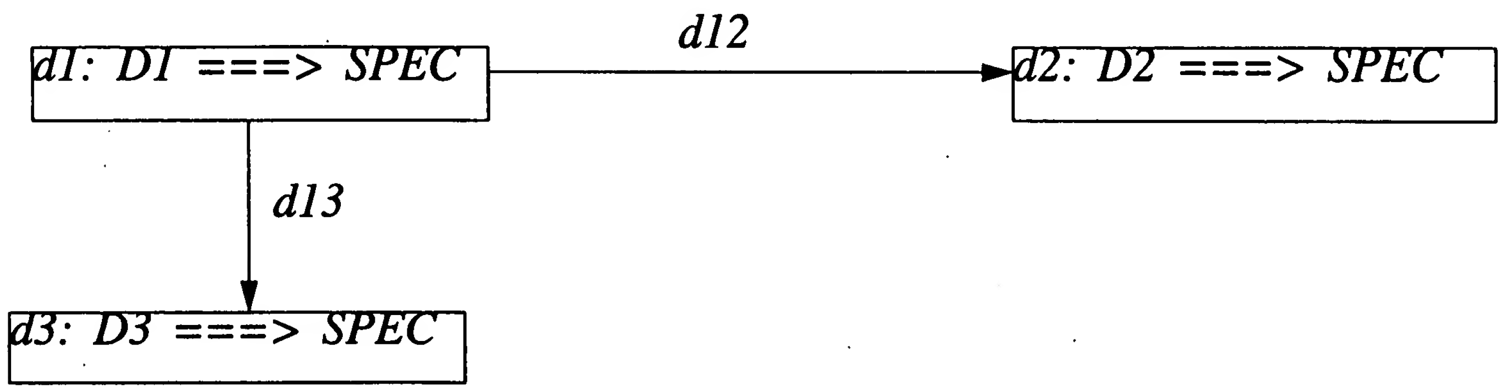
$${}^{b}_{A}\, i+ii+iii = \left\{ \begin{array}{l} Sp_i \cdot S_1 \longrightarrow S_2 \\ Sp_{iii} \cdot S_1 \longrightarrow S_2 \\ Sp_i \cdot f_1 \longrightarrow f \\ Sp_{iii} \cdot f_1 \longrightarrow g \\ Sp_i \cdot f_2 \longrightarrow g \end{array} \right\}$$

Fig 21(F) Example of Diagram Extension (cont)

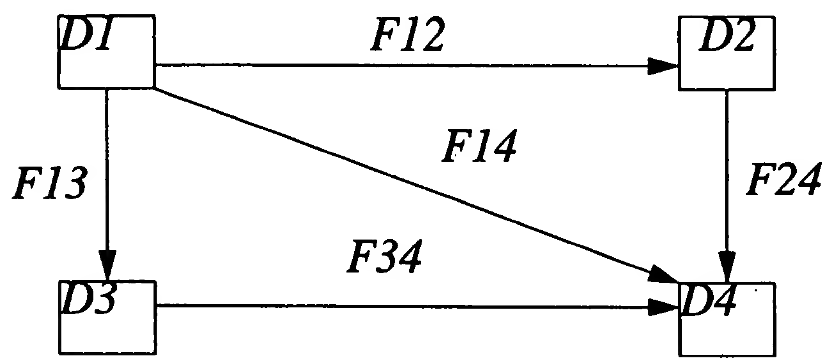
(5)

After finishing the extension for each diagrams, let us use the following example:

Original diagrams:



Its underlying shape categories, shape functors and the colimit are:

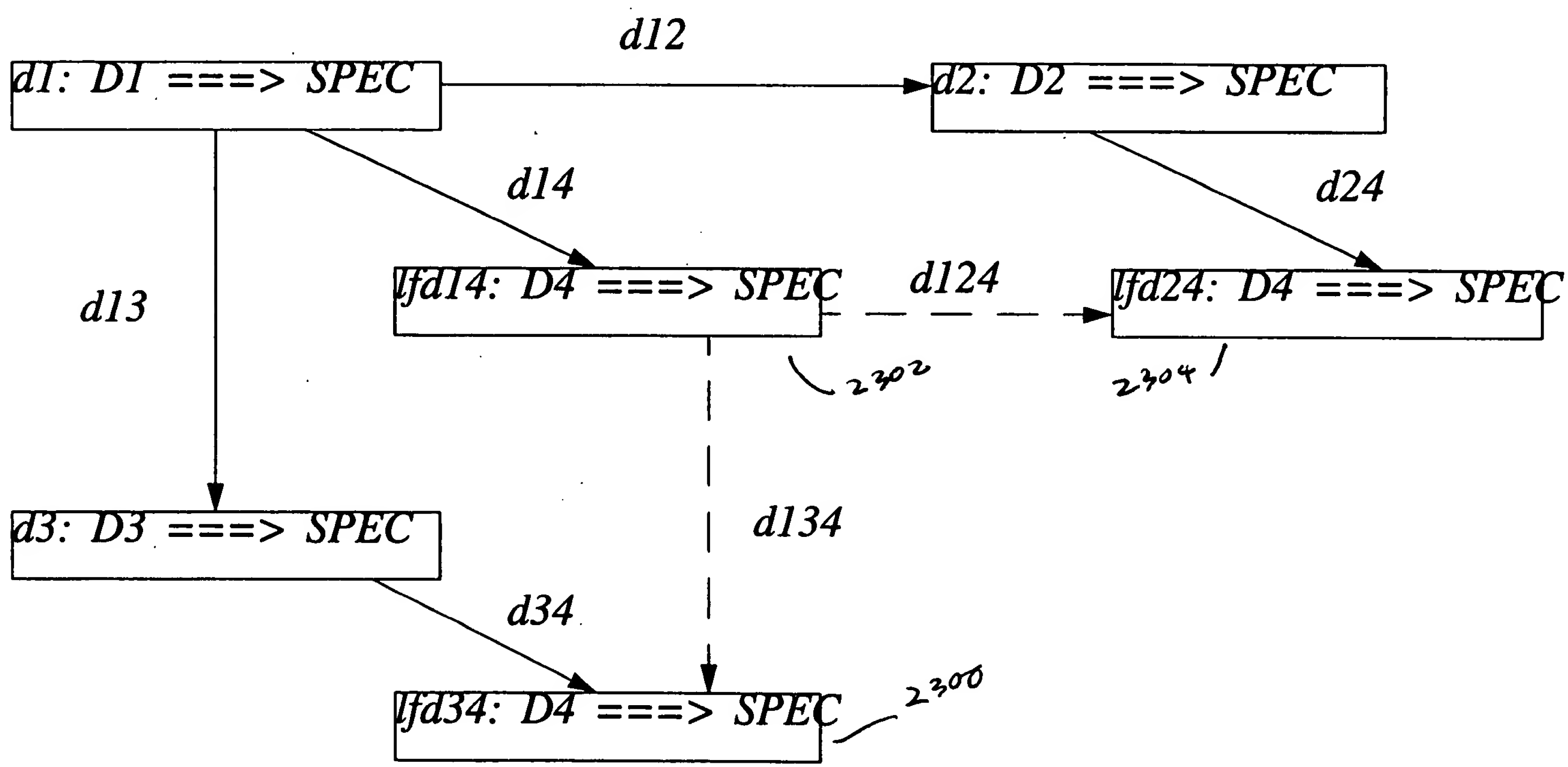


Part III

Fig. 22

09565179.091909

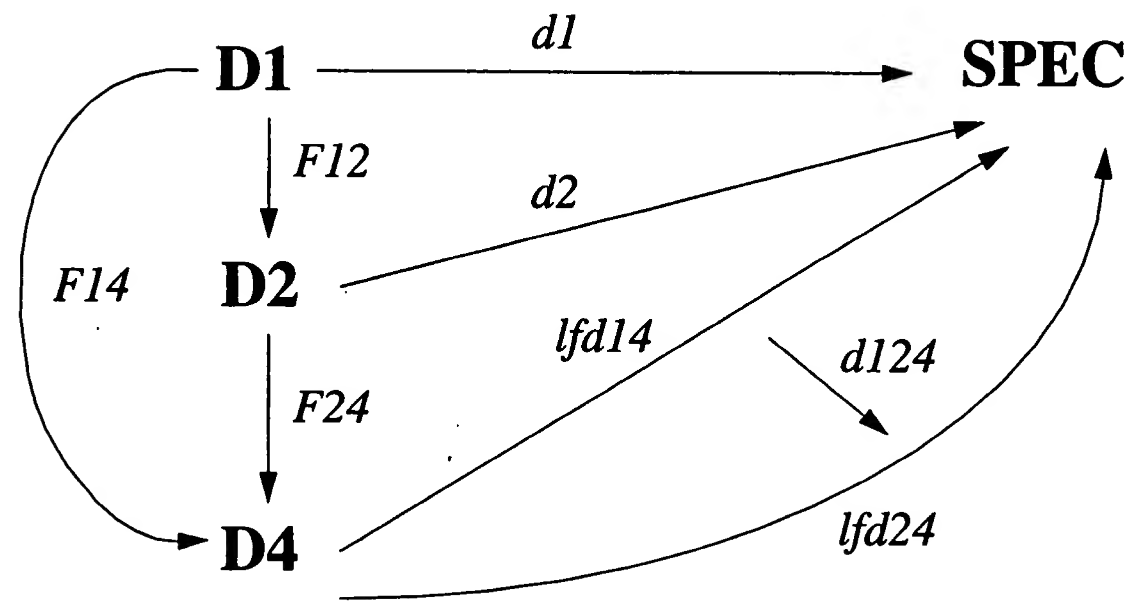
Extended diagrams:



The last algorithm step we are missing for constructing the diagram colimits is the diagram morphisms between extended diagrams. For example, the diagram morphism d124 and d134 (dotted lined arrows in above figure) are the ones needed.

Suppose lfd14 and lfd24 are two extensions of d1 and d2, given the colimit of the shape categories as D4. We would have the following picture.

Fig. 23

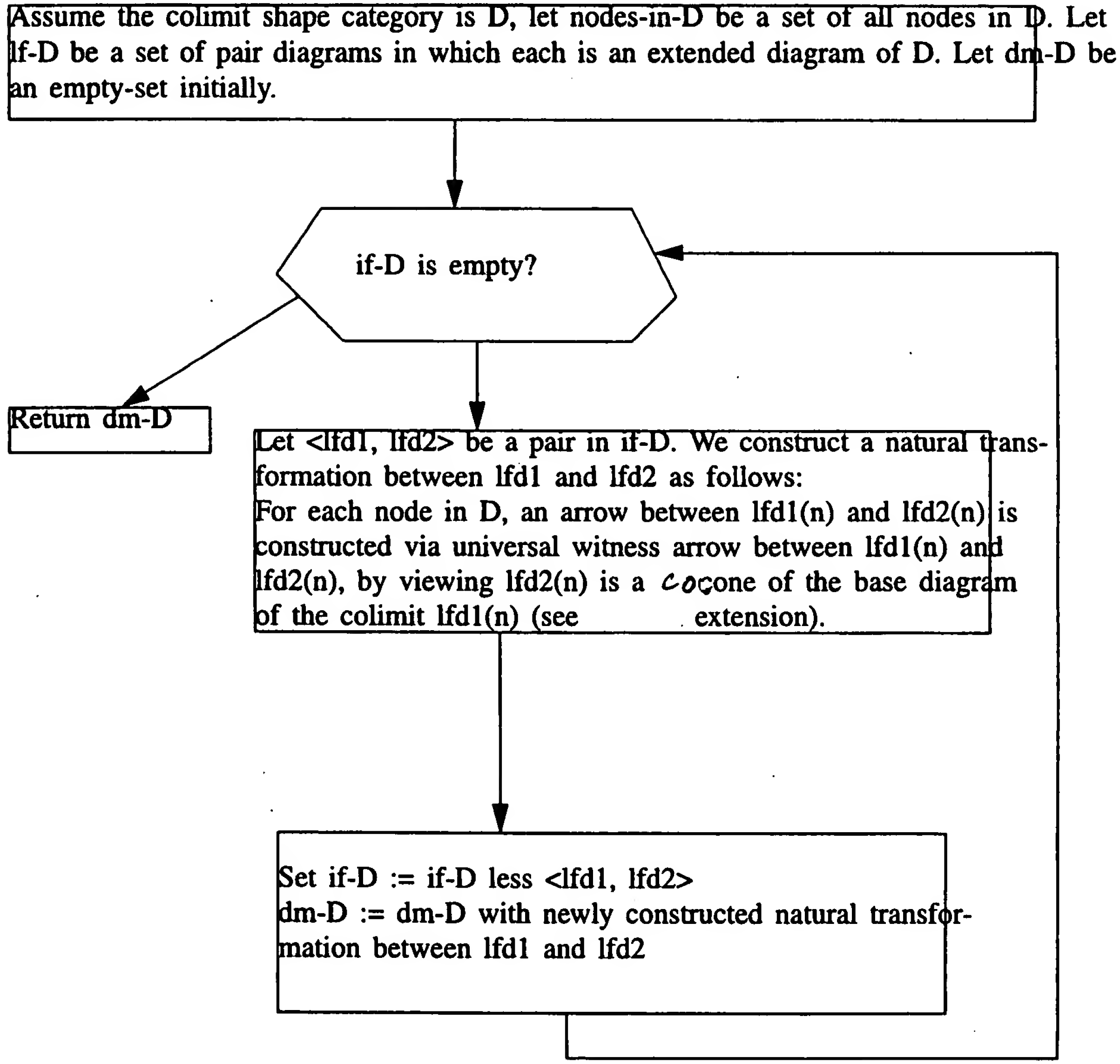


A morphism between lfd14 and lfd24 is a natural transformation which maps each node of D4 to an arrow in SPEC. We do th the universal construction of witness arrows.

For any node ni in D4, we have F14(ni) = F12 o F24(ni). Let Sp1ni and Sp2ni two shape categories used for constructing a mapping for ni in its extension of d1 and d2, respectively, then we can have a shape function between Sp1ni and Sp2ni (inclusion, basically). That induces a diagram morphism between the base diagrams for the target of ni in lfd14 and lfd24, respectively. By imposing that diagram morphism and cocone morphism, we can get an unique arrow between lfd14(ni) and lfd24(ni). Repeating this process we construct a natural transformation between lfd14 and lfd24. Similarly, we can do this for any two extended diagrams.

The following flowchart is the algorithm for constructing a diagram morphism between two extended diagrams.

Fig. 24



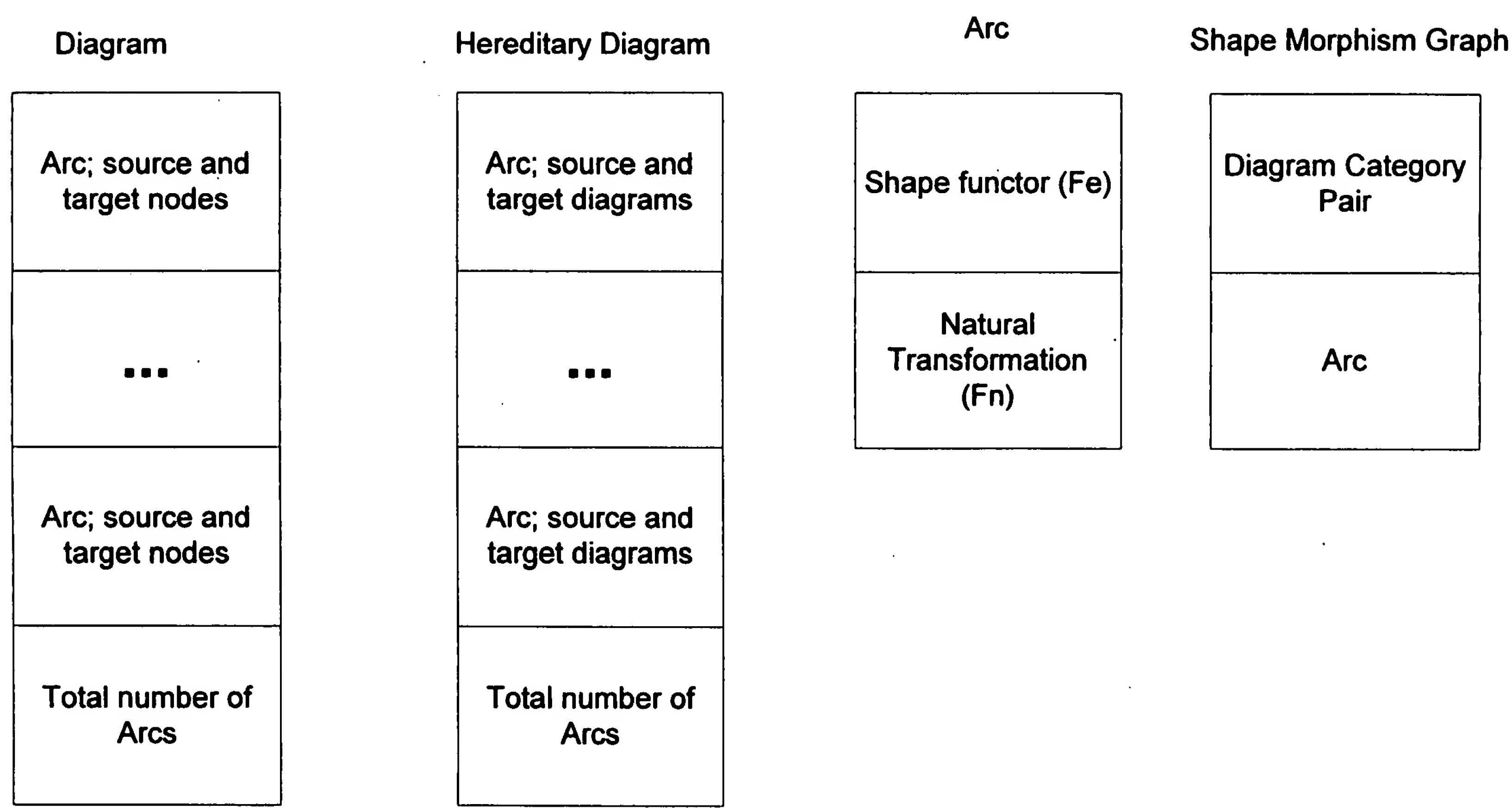
Assume the colimit shape category is D, let nodes-in-D be a set of all nodes in D. Let lf-D be a set of pair diagrams in which each is an extended diagram of D. Let dm-D be an empty-set initially.
if-D is empty?
Return dm-D
Let <lfd1, lfd2> be a pair in if-D. We construct a natural transformation between lfd1 and lfd2 as follows:
For each node in D, an arrow between lfd1(n) and lfd2(n) is constructed via universal witness arrow between lfd1(n) and lfd2(n), by viewing lfd2(n) is a cocone of the base diagram of the colimit lfd1(n) (see extension).
Set if-D := if-D less <lfd1, lfd2>
dm-D := dm-D with newly constructed natural transformation between lfd1 and lfd2

Fig. 25

The final step is to complete the colimit of the extended diagrams. The colimit is determined by computing the pointwise colimits over corresponding nodes in the extended diagrams. The morphisms are computed uniquely using universality of the pointwise colimits.

$$\begin{tikzcd}
\text{Extended diagram of d1} \arrow[r, Rightarrow] \arrow[d, Rightarrow] & \text{Extended diagram d2} \arrow[d, Rightarrow] \\
\text{Extended diagram d3} \arrow[r, Rightarrow] & \text{Colimit of Diagrams}
\end{tikzcd}$$

Taking Pointwise Colimit of Extended Diagrams (Can be done, since extended diagrams are all the same shape)
Fig. 26



Examples of Data Structures used in the Example Implementation

Fig. 27

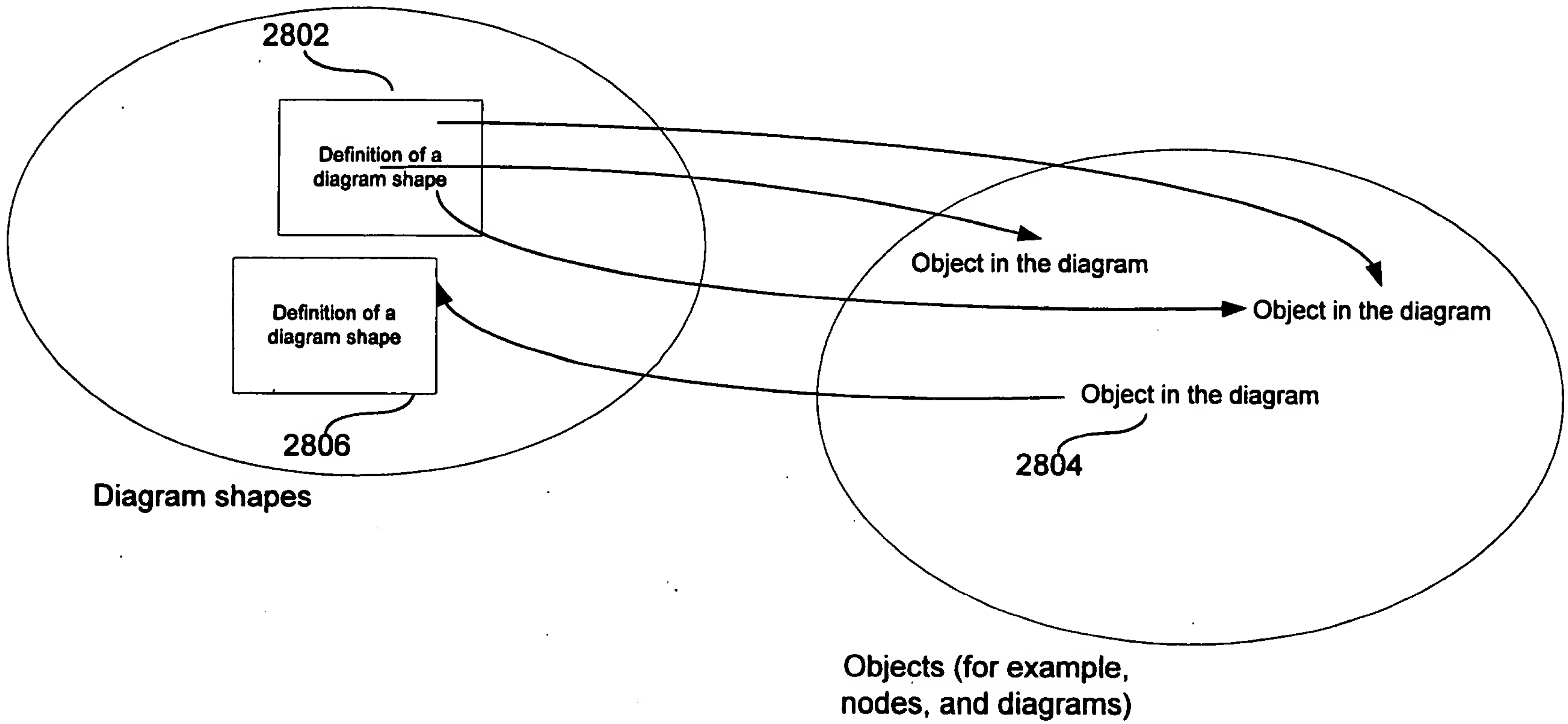

2802
Definition of a diagram shape
Definition of a diagram shape
2806
Diagram shapes
Object in the diagram
Object in the diagram
Object in the diagram
2804
Objects (for example, nodes, and diagrams)

Fig. 28

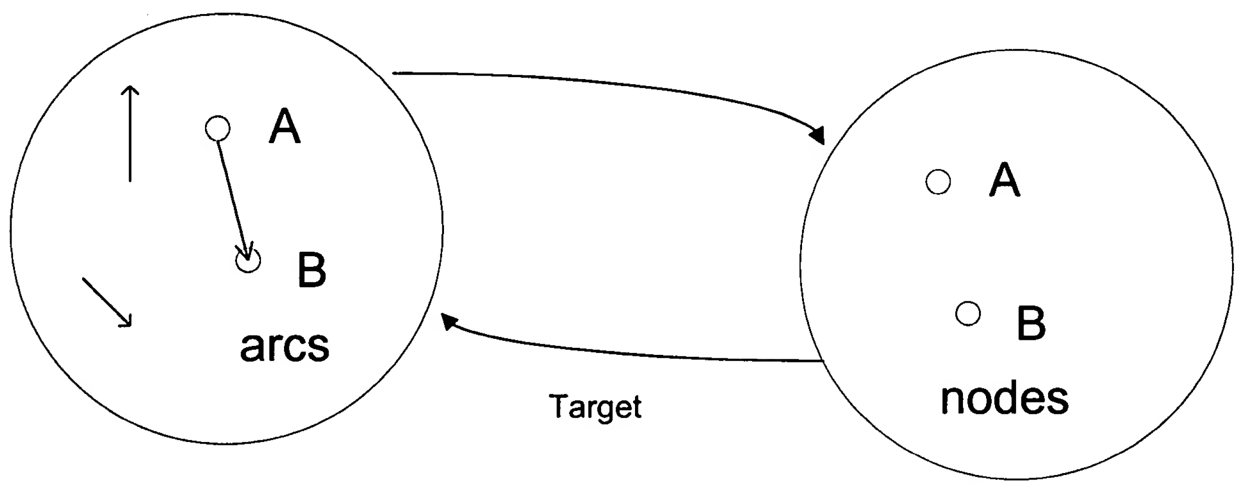


Fig. 29